T2K Capabilities, Measurement and Plans

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For the T2K Collaboration

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UNIVERSITY of HOUSTON

T2K

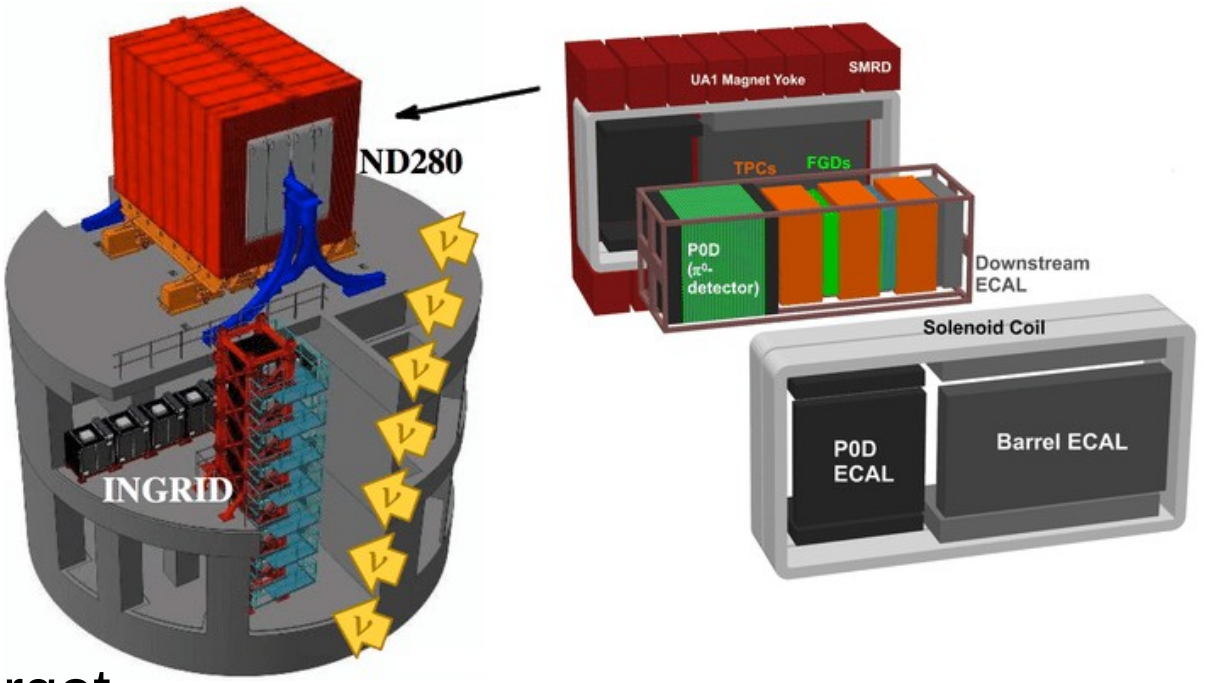
Overview

- T2K: Detectors and Flux
- General Strategies
- Pion Production Measurements
  - Hydrocarbon Target (FGD1)
  - Water Target (FGD2 – FGD1)
  - CH, H_2O, Brass (P0D)
  - On axis on CH, H_2O, Fe (INGRID)
- Looking to the future
  - Ongoing measurements
  - Prospects for the ND280 upgrade

Not covered (due to time):
Coherent
Neutral pion
Multi-pion

ND280

- ND280 is the T2K off-axis ND
- Same off-axis angle as SK (2.5°)
- Contained in a 0.2 T magnetic field
- Three CH and H_2O target modules
  - P0D (water-in / water-out)
  - FGD1 (CH)
  - FGD2 (CH+H_2O)
- Three TPC trackers downstream from each target module



ND280 and the P0D

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  - FGD1 (CH)
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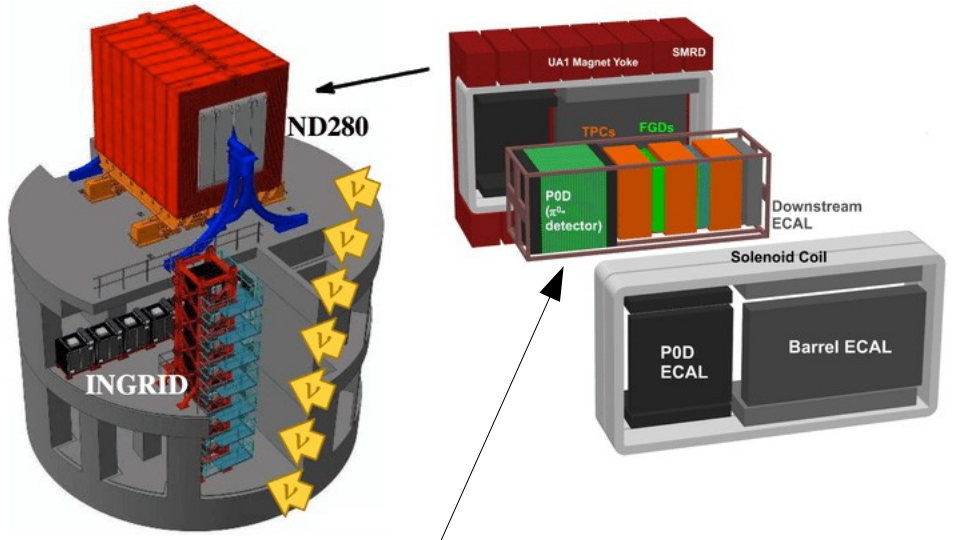

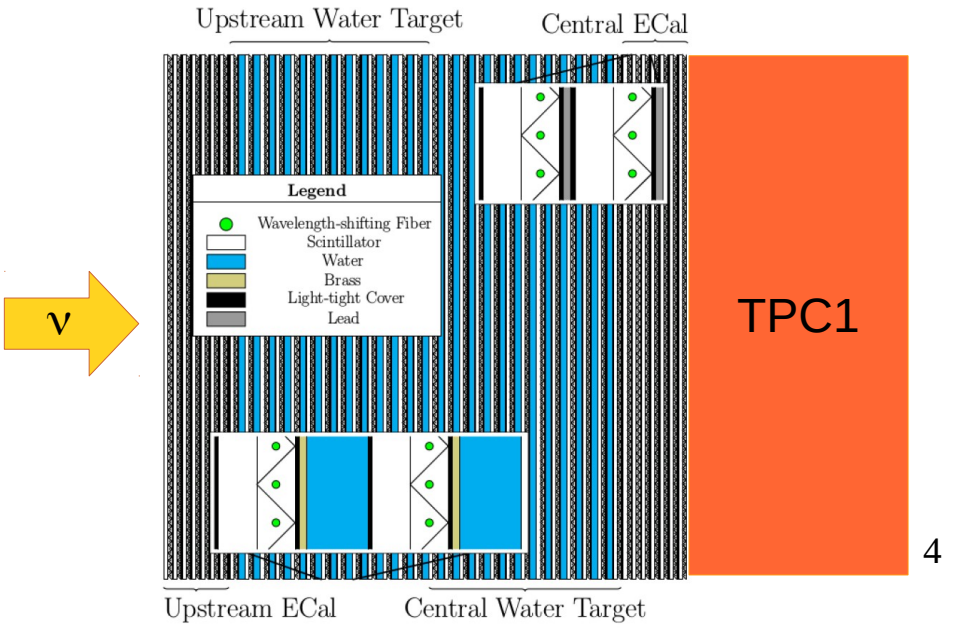

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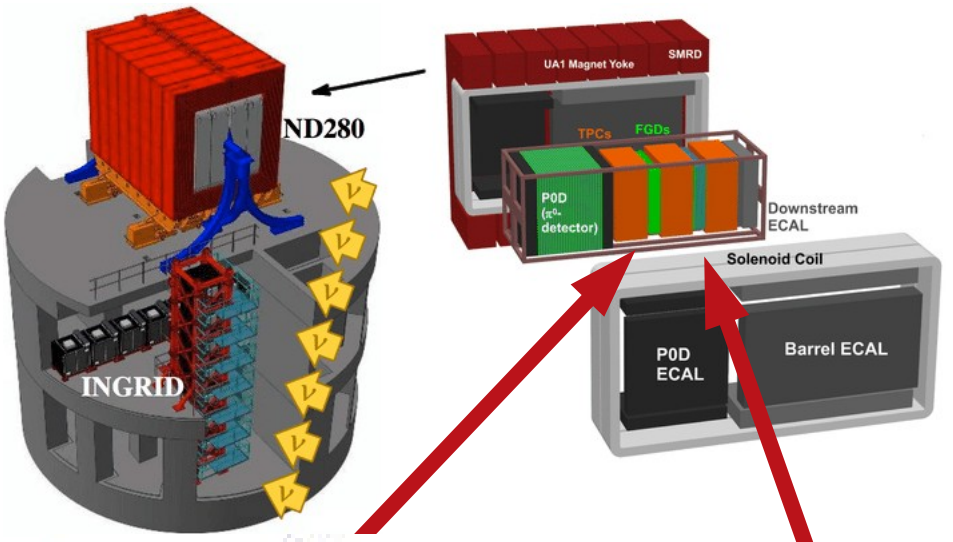
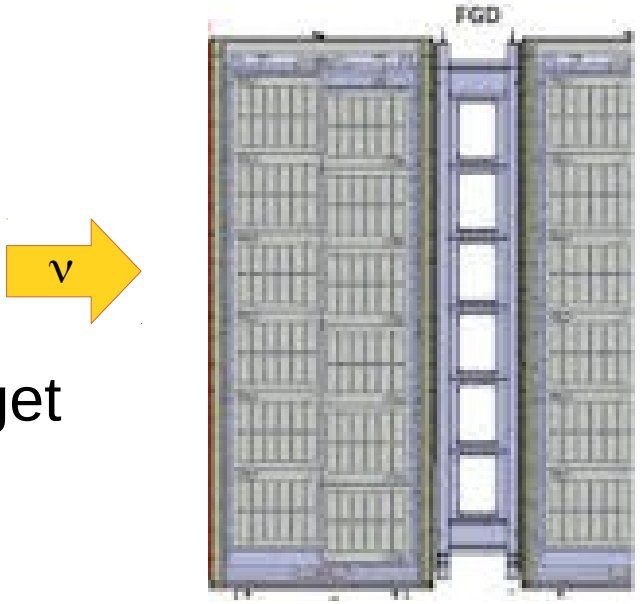
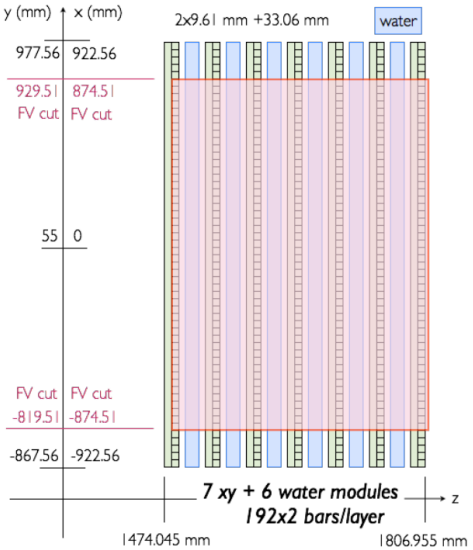
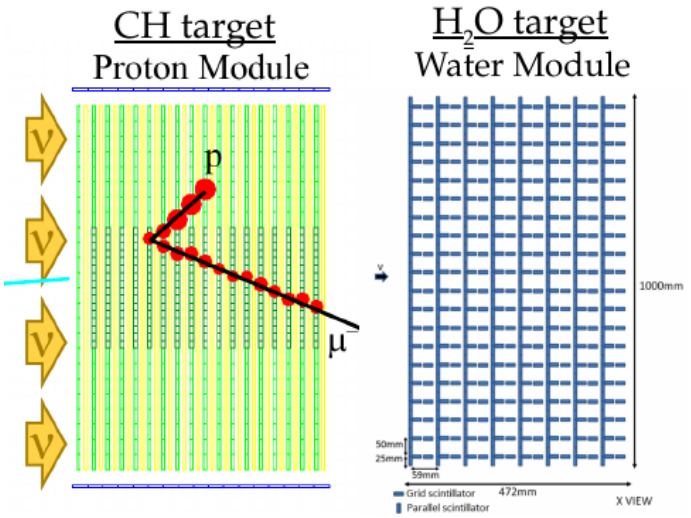


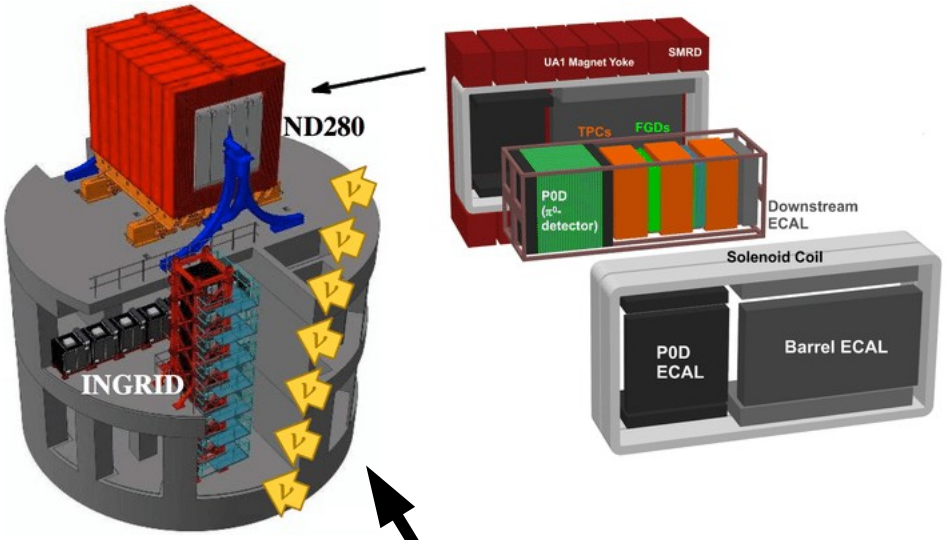


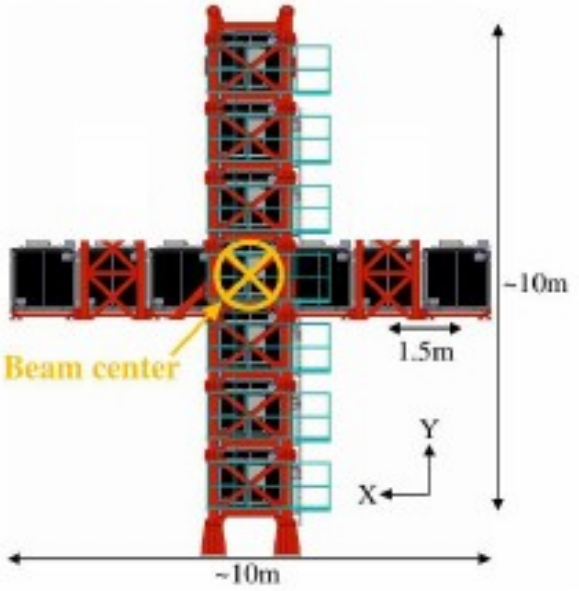


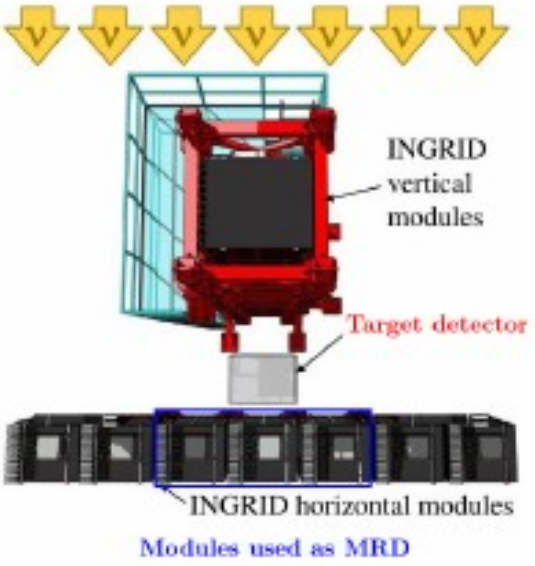
INGRID

- INGRID is the T2K on-axis ND
- Main Purpose:
  - Monitor the beam stability
  - Beam direction
  - Time dependence
- Fe plates with CH scintillator bars
- Physics detectors:
  - Proton Module: all CH scintillator
  - Water Module: CH and H_2O



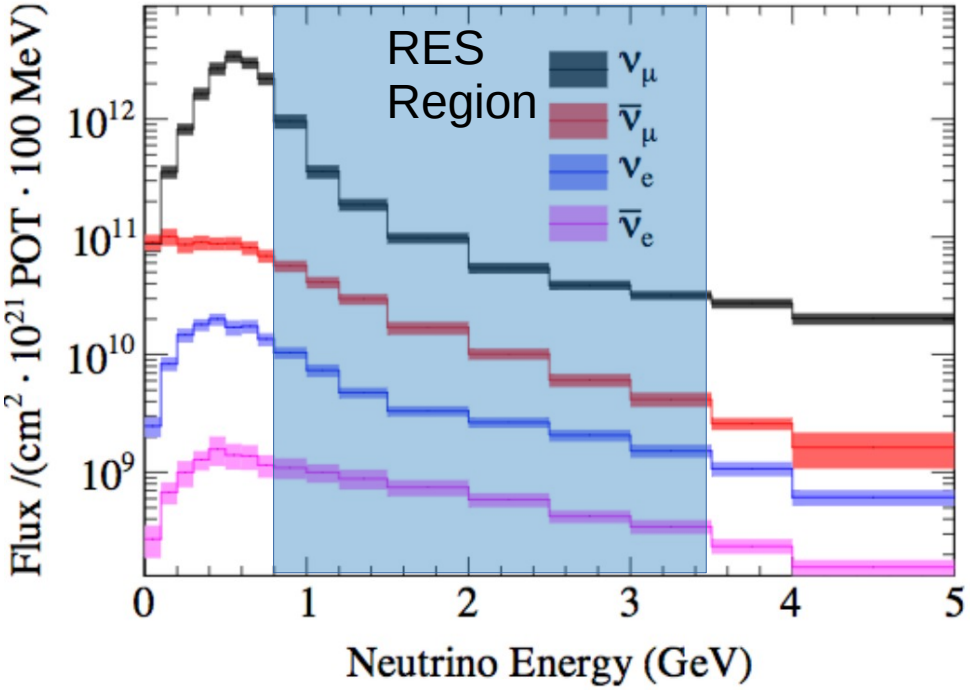


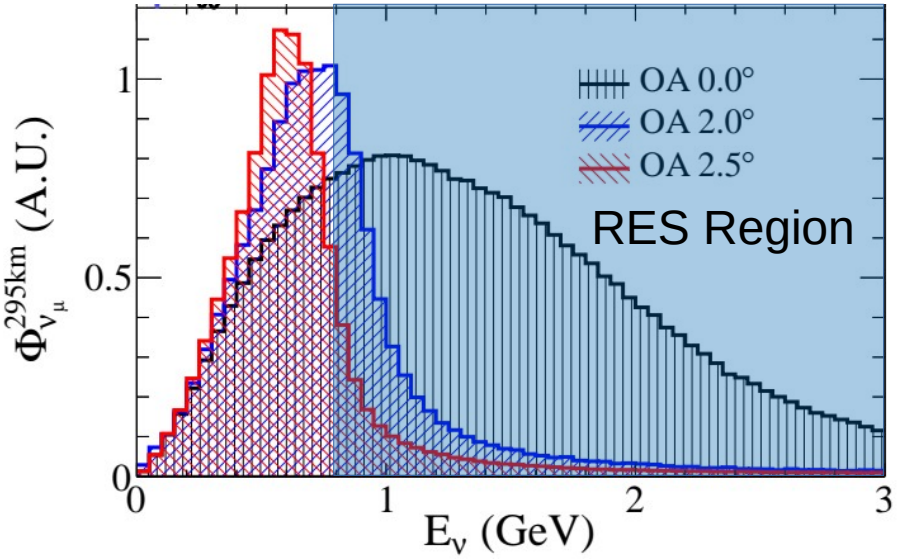


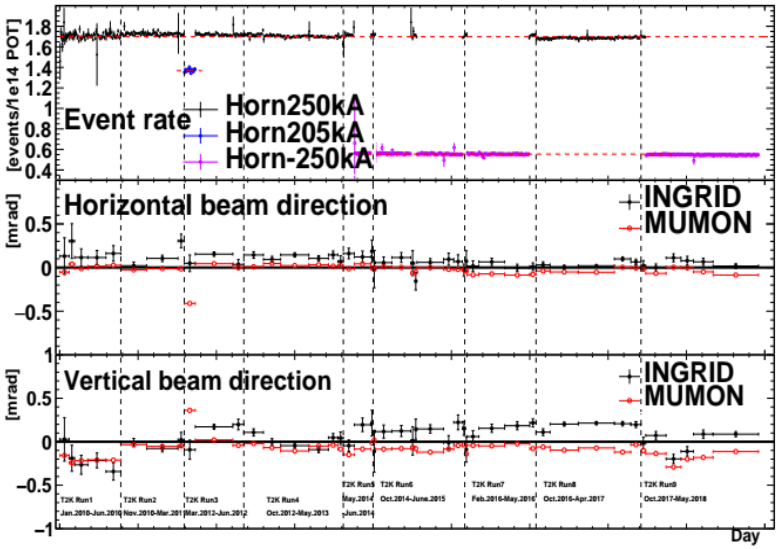


The T2K Flux

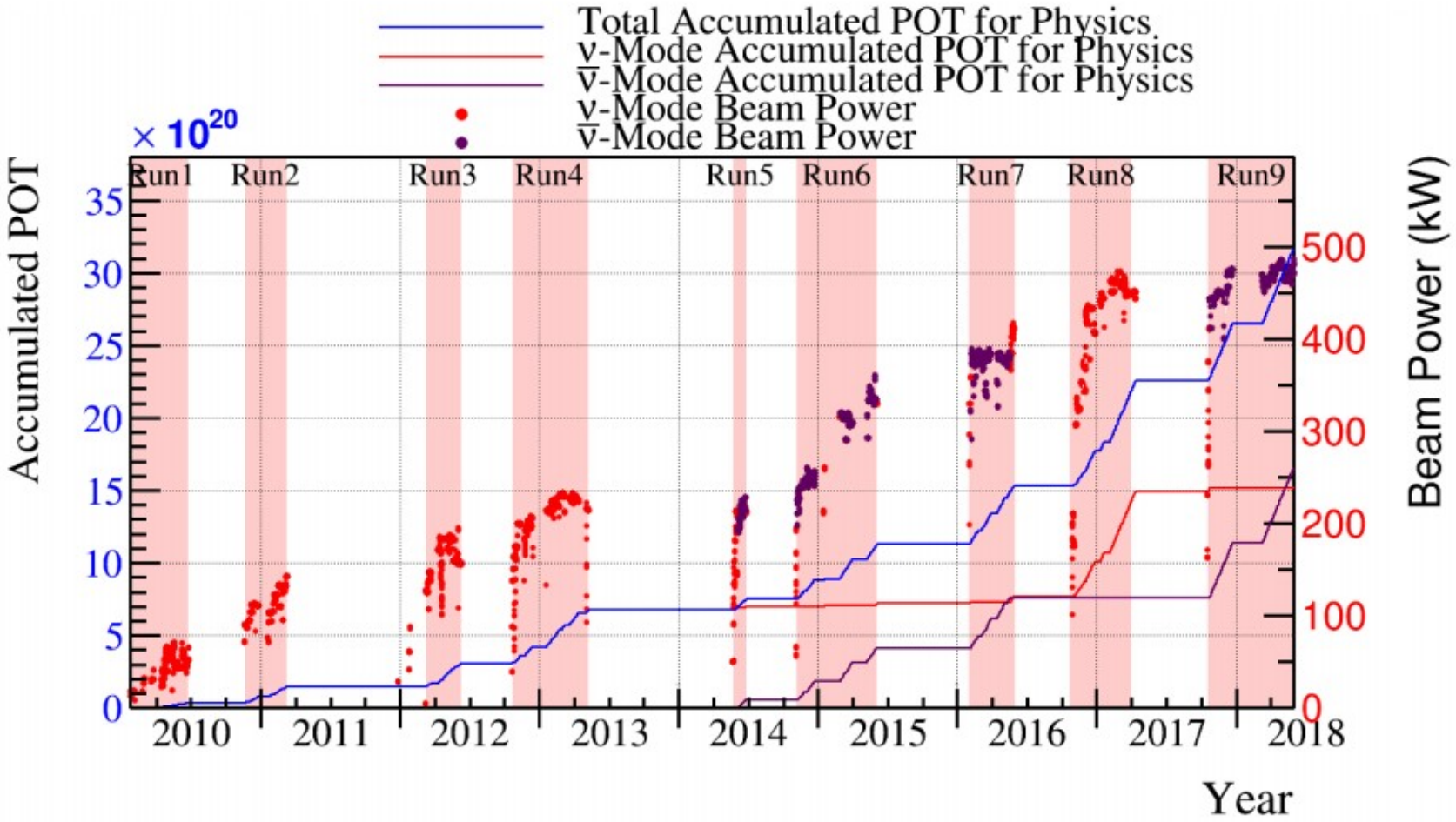
- Off-axis flux (2.5º) flux peaked at 600 MeV
- On-axis peak ~1 GeV
- Contamination from wrong sign, ne
- Stability monitored by INGRID







Data Samples



- Existing results: up to Run 4
- Next-gen results: up to Run 9

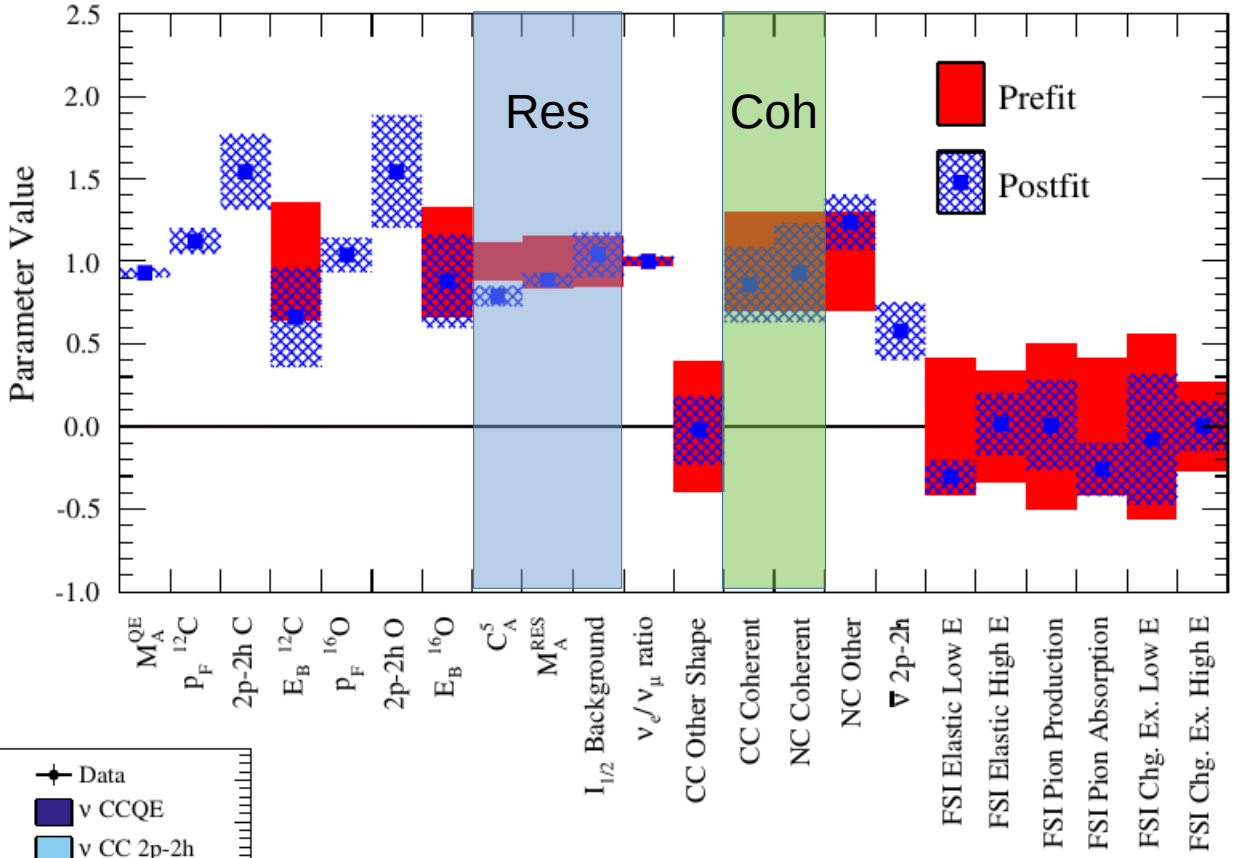
ν-mode 1.51×10^{21} (47.83%)
$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

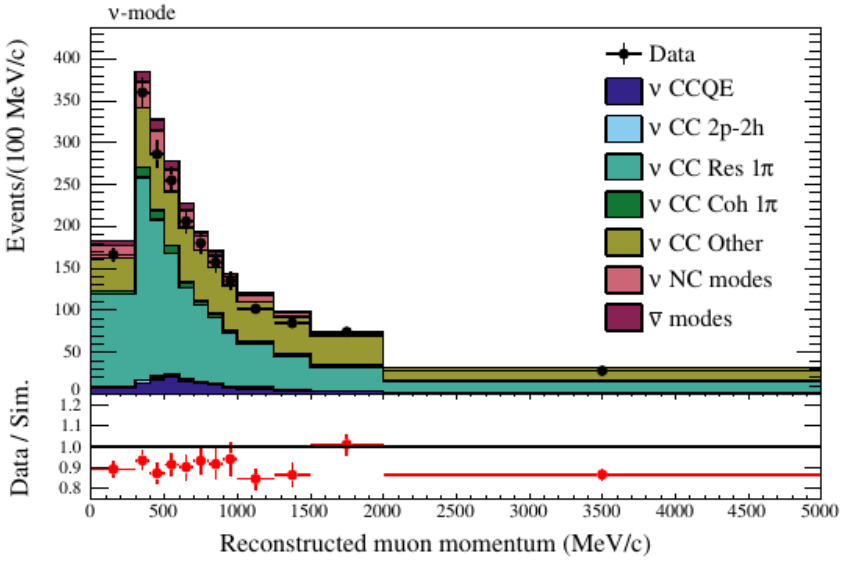
General Strategies

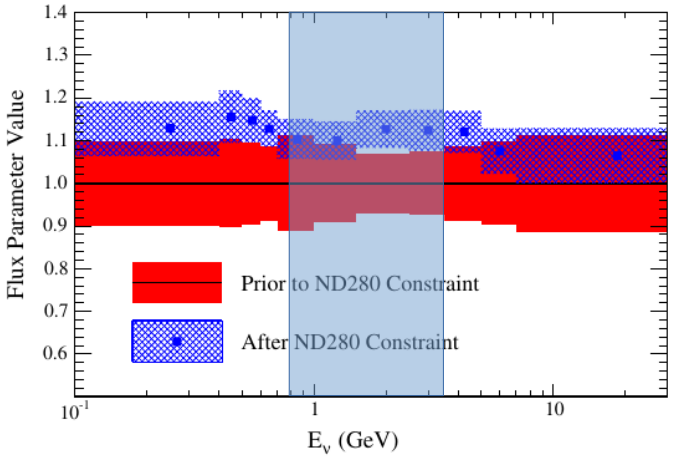
- Flux integrated differential measurements
- Restricted phase space
- Fit backgrounds using sidebands
- Background shape parameters taken from oscillation analyses
  - Background params used in xsec extraction
  - Signal params used in eff correction
- Flux covariance (bins of Eν)
- Detector covariance in analysis bins
- SI systematics
- To unfold or not to unfold?
- Fake data studies:
  - Test fitter machinery
  - Evaluate bias
  - Validate error band coverage (of models)

Pion Production in the OA

- Main xsec systematics designed for the OA
- Single π production samples identified
- Data is below prediction
- Fit pulls up flux







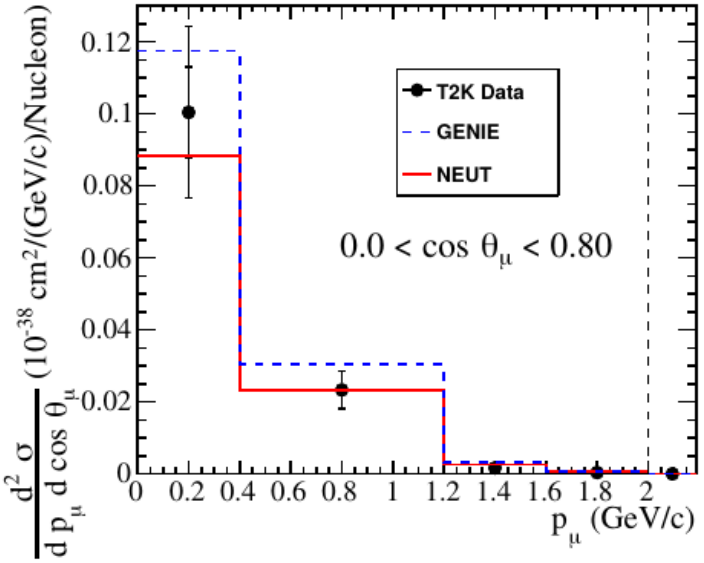
CC1π^+ in FGD1 (CH)

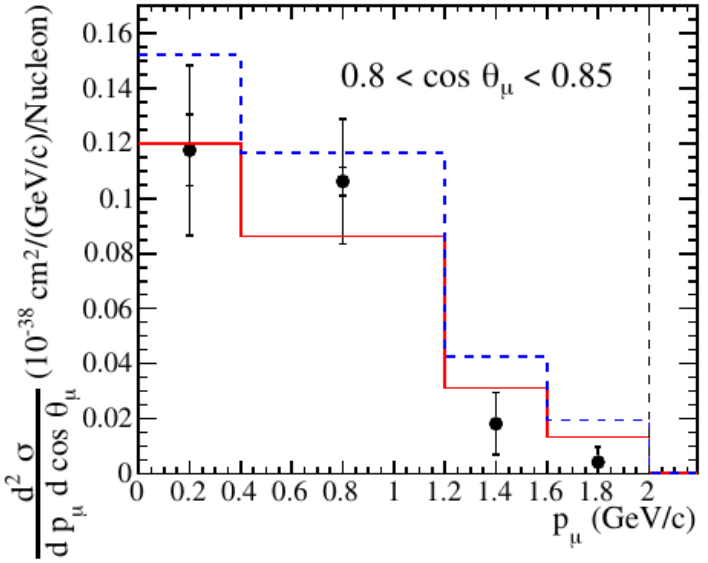
- Differential cross section in 7 kinematic variables
- Independent measurements
  - Define phase space for each
  - Fit same data with same set of parameters
- Sideband samples
  - Constrain CC0π and DIS
  - Shape and normalization parameters
- Unfolding:
  - D'Agostini
  - One iteration

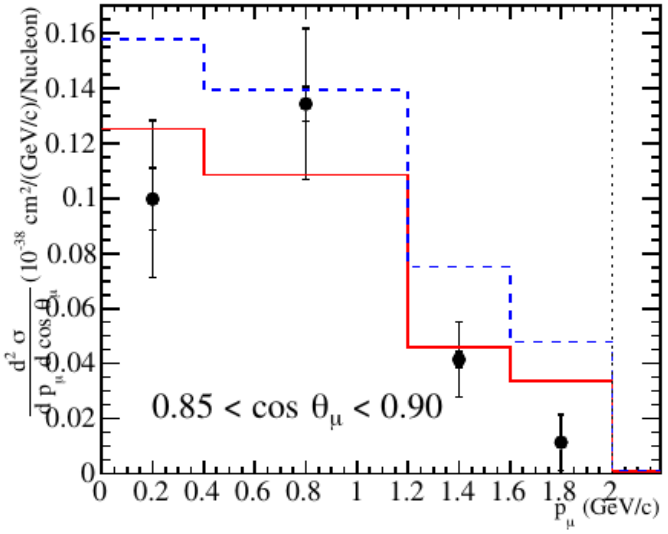
TABLE V. Definition of the phase space restrictions used for the differential cross section measurements.

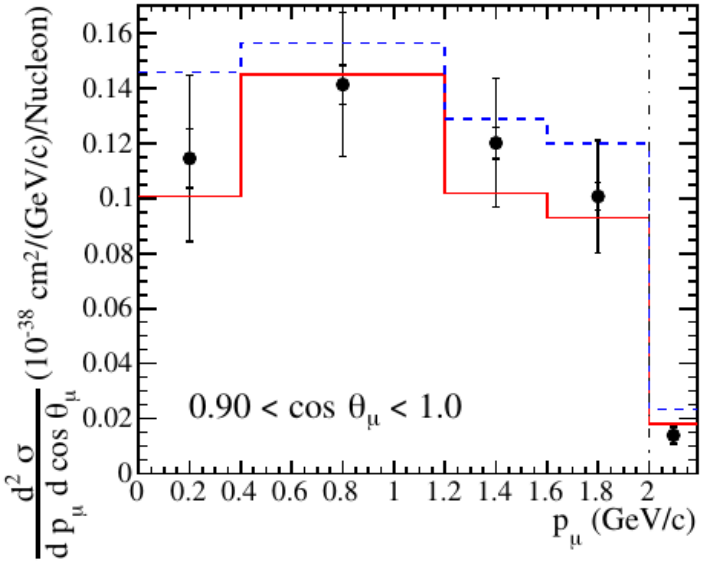
Observable	$\cos\theta_\mu > 0$	$\cos\theta_\mu > 0.2$ $p_\mu > 0.2\ GeV/c$	$\cos\theta_\pi > 0.2$	$\cos\theta_\pi > 0$	$p_\pi > 0.2\ GeV/c$	Michel Electron
$d^2\sigma/dp_\mu d\cos\theta_\mu$	Y					Y
$d\sigma/dQ^2$		Y	Y		Y	
$d\sigma/dp_\pi$		Y	Y			
$d\sigma/d\theta_\pi$		Y		Y	Y	
$d\sigma/d\theta_{\pi\mu}$		Y	Y		Y	
$d\sigma/d\phi_{Adler}$		Y	Y		Y	
$d\sigma/d\theta_{Adler}$		Y	Y		Y	

Results: $d\sigma^2/dp_\mu d\theta_\mu$



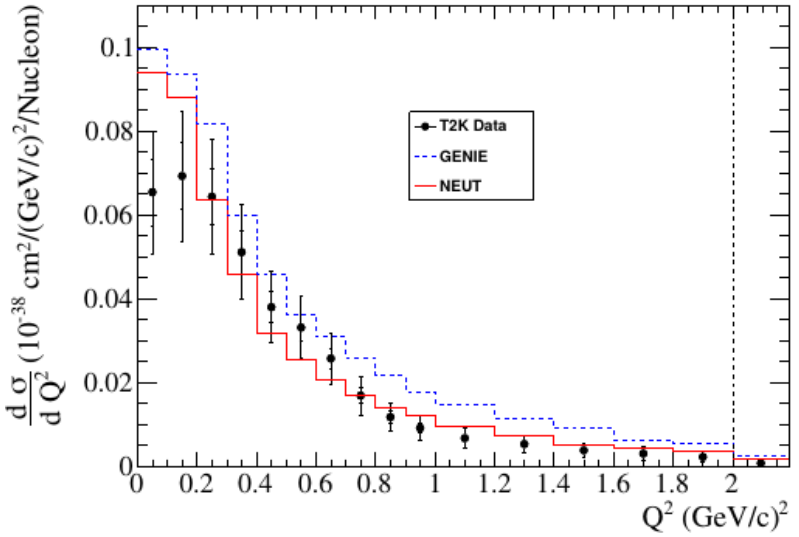


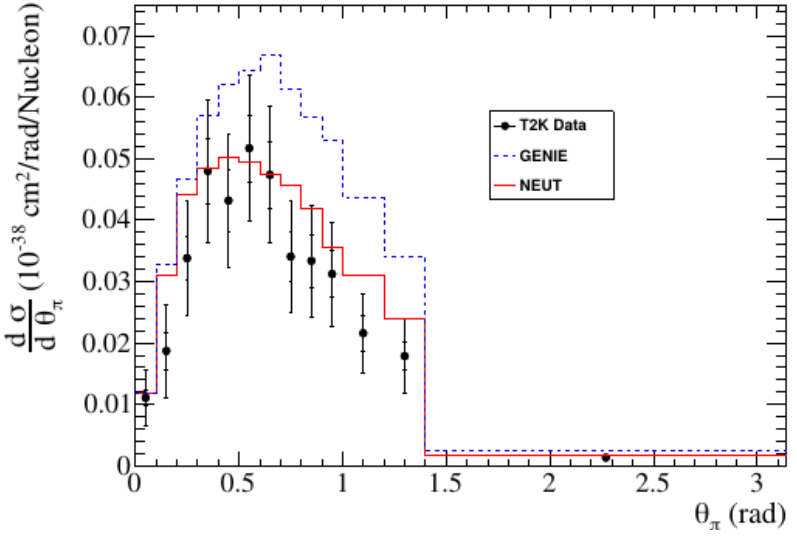


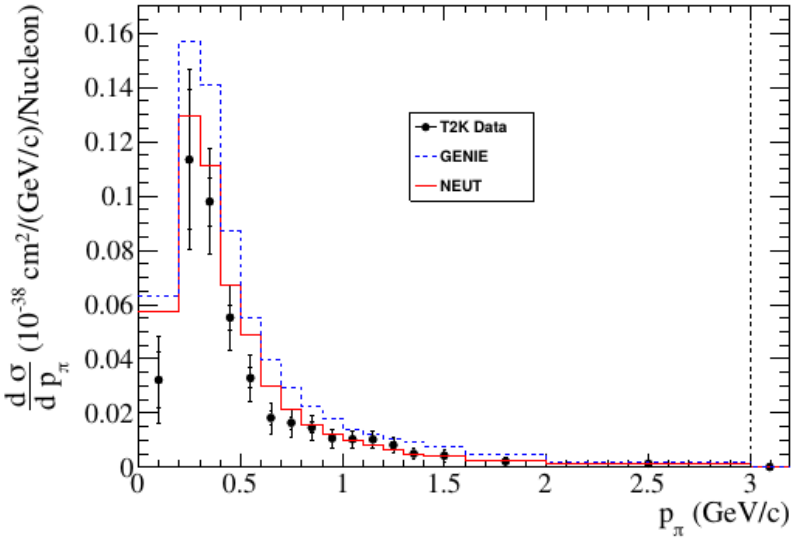


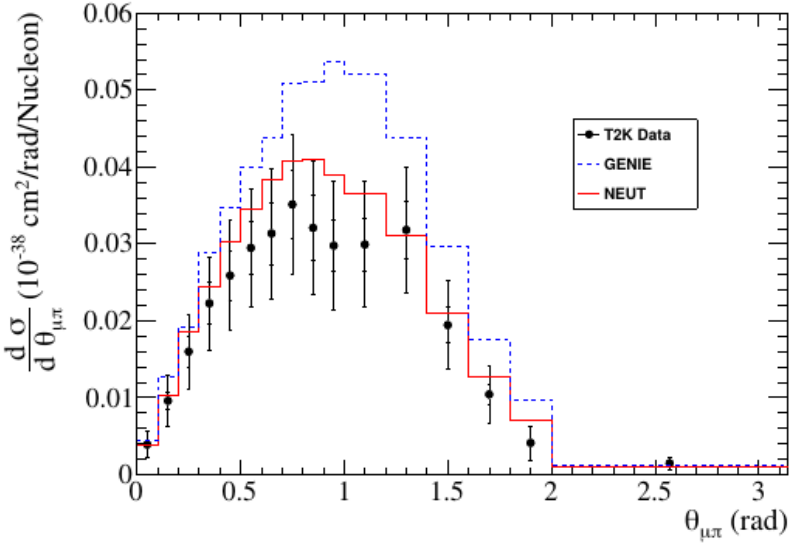
- Includes Michele electron π tag sample
- Extends π phase space to low momentum
- Efficiency is non-zero, but not flat either
- Only PS restriction: $\theta_\mu > 0$
- Relatively good agreement with data

Results: $d\sigma/d(Q^2,\theta_\pi,p_\pi,\theta_{\mu\pi})$



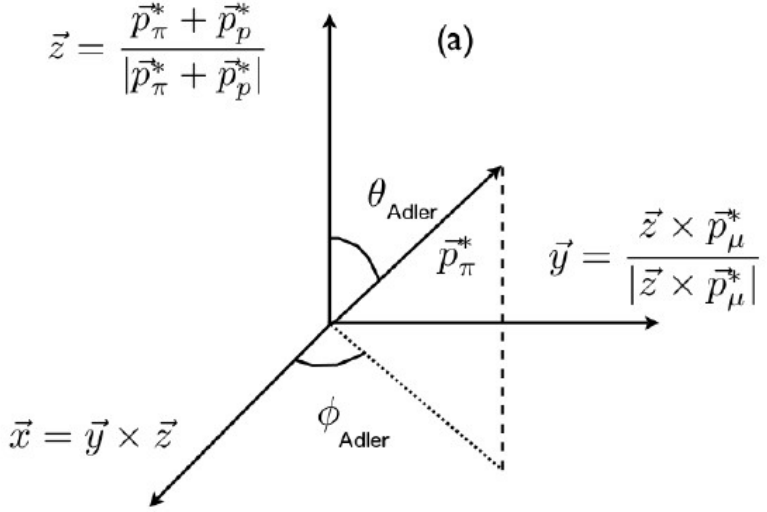


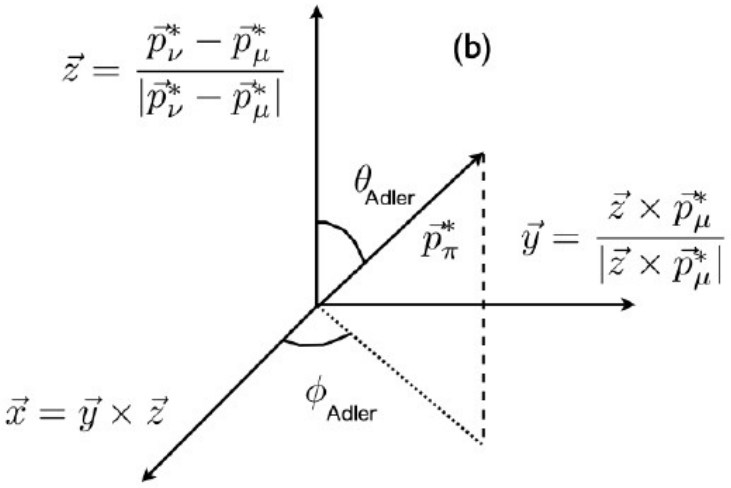


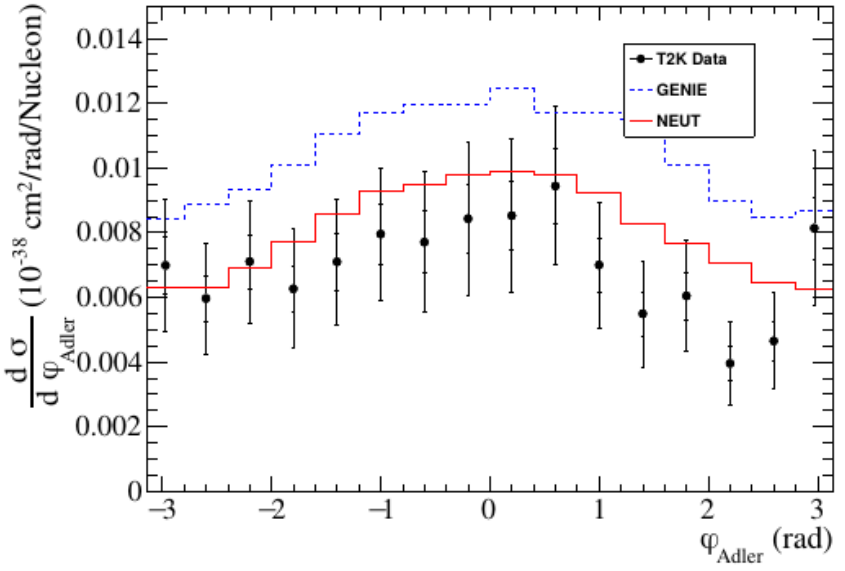


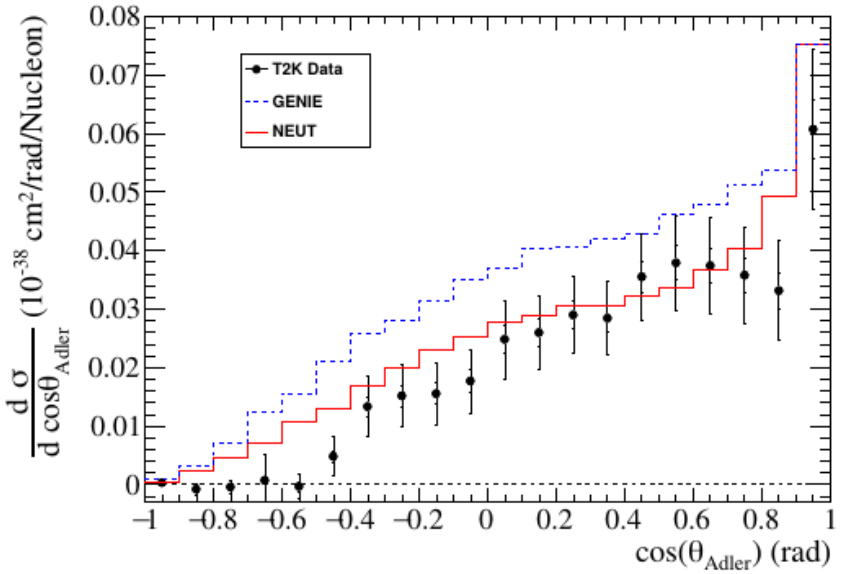
- PS restrict "hidden" variables
- Observe low Q^2 suppression
- Results that restrict low p_π fall below predictions

Results: $d\sigma/d(\phi_{Adler},\theta_{Adler})$









CC1π^+ in FGD2 (H_2O)

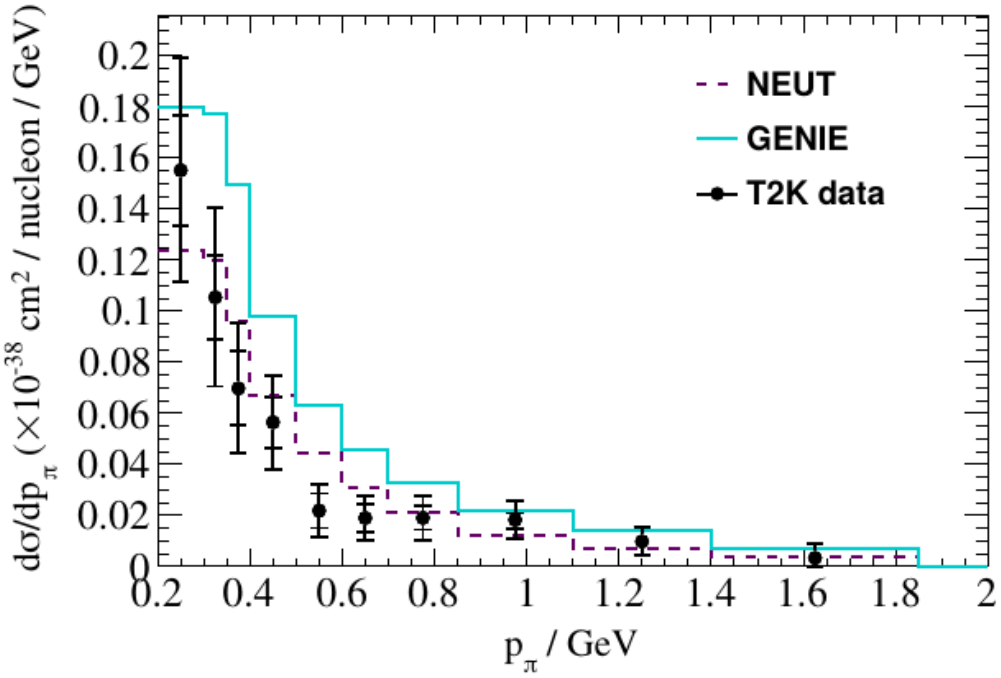
- Differential cross section in μ and π kinematics
- Independent measurements
  - Phase space same for each
  - Fit same data with same set of parameters
- Sideband samples
  - Constrain DIS and CH-xsec
  - Shape and normalization parameters
- Unfolding:
  - D'Agostini
  - One iteration

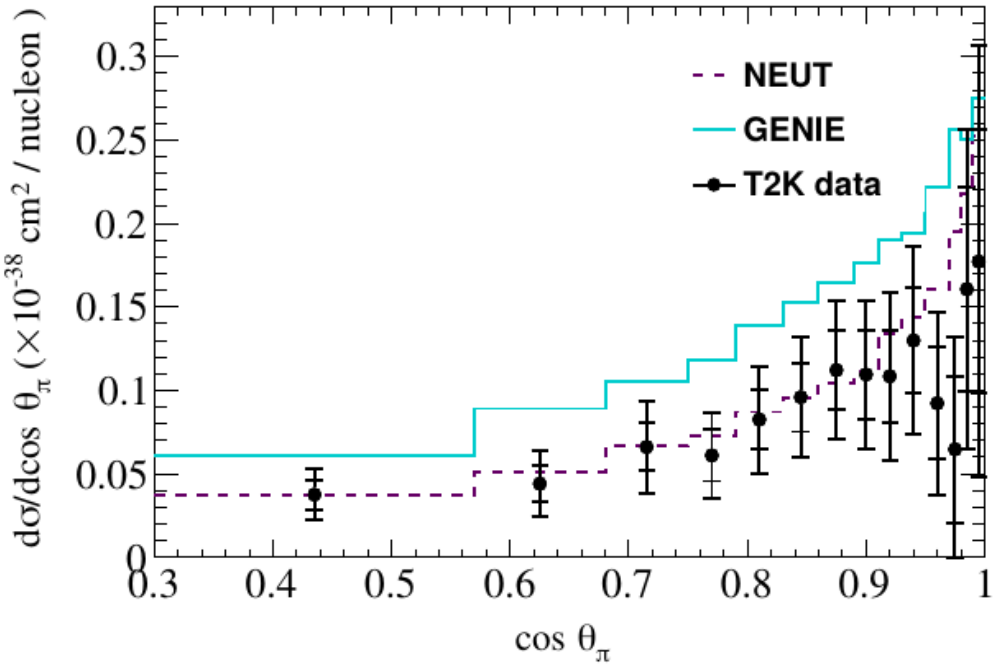
Phase Space Restrictions

$p_\mu > 200$ MeV/c $\cos(\theta_\mu) > 0.3$

$p_\pi > 200$ MeV/c $\cos(\theta_\pi) > 0.3$

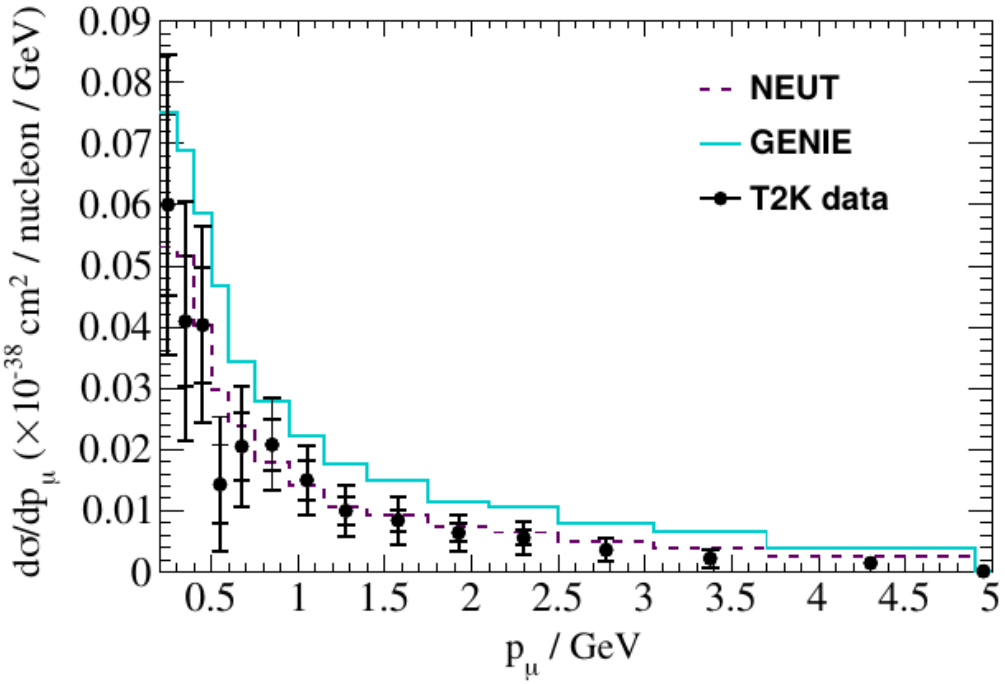
Results: π kinematics

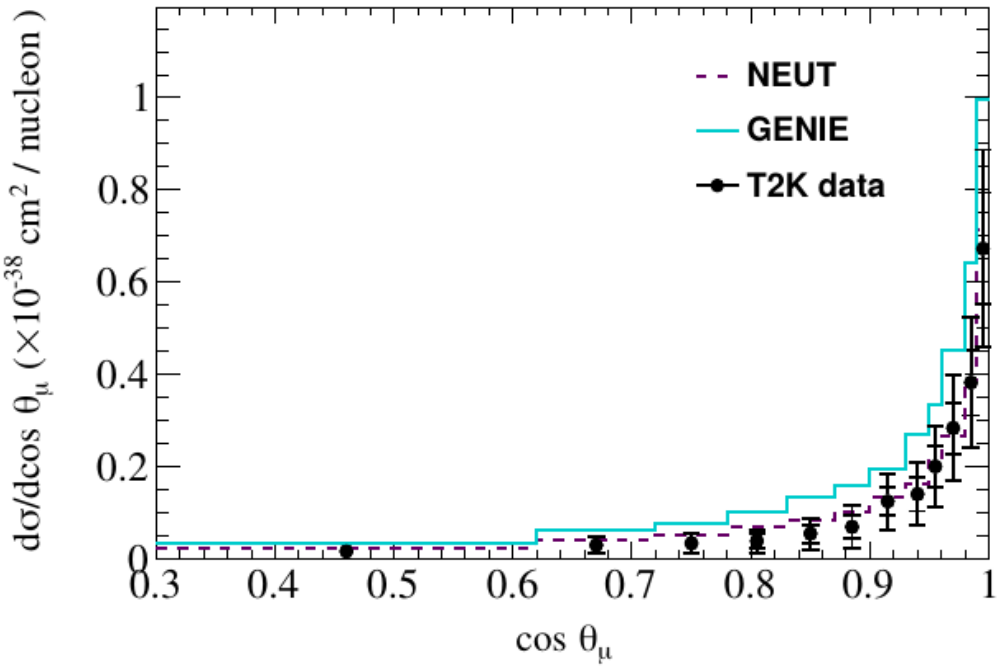




- Momentum:
  - Agrees well for p_π > 700 MeV
  - Below prediction 300 < p_π < 700 MeV
  - Above prediction p_π < 300 MeV
- Angle:
  - Agrees well for $\cos\theta_\pi$ < 0.94
  - Large dip above $\cos\theta_\pi$ > 0.94
  - Gets a bit better $\cos\theta_\pi$ > 0.98

Results: μ kinematics



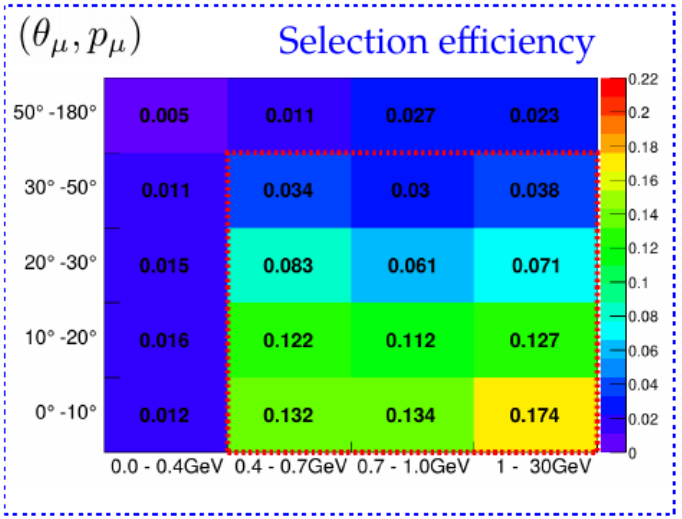


- Momentum:
  - Shape agrees well
  - Just below NEUT predeiction
  - Well below GENIE
- Angle:
  - Shape agrees well
  - Just below NEUT predeiction
  - Well below GENIE

CC1π^+ in INGRID (CH&$H_2$0)

- Differential cross section in μ kinematics
- Double differential fit
- Fit CH and CH + $H_2$0
- No magnetic field
- Good momentum resolution for contained tracks

- Sideband samples
  - Constrain CC0π and CH-xsec
  - No DIS sample
  - Shape parameters
- Unfolding:
  - D'Agostini
  - Data based convergence criteria (~10 iterations)

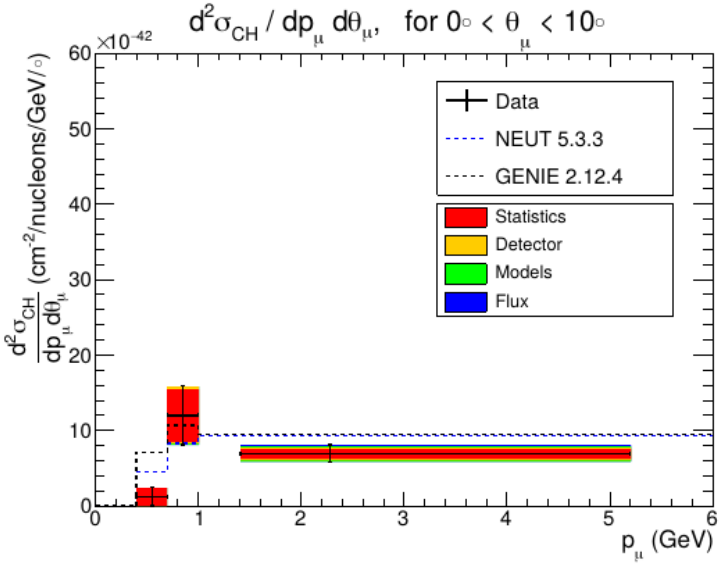


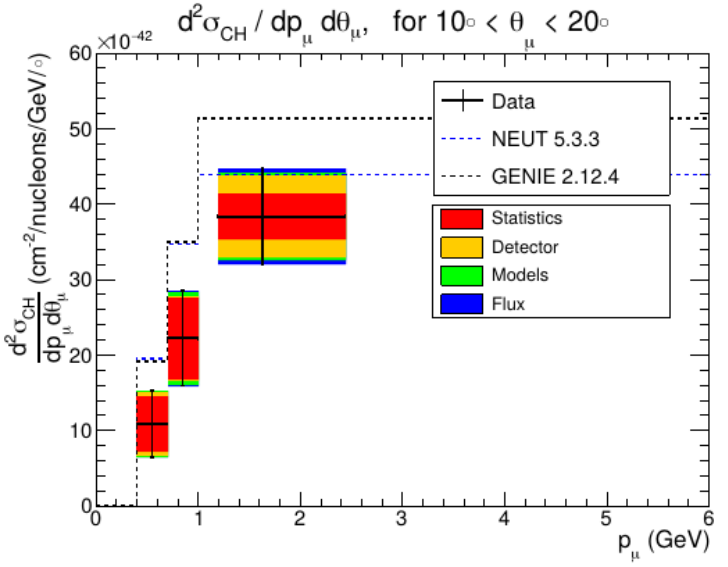
Phase Space Restrictions

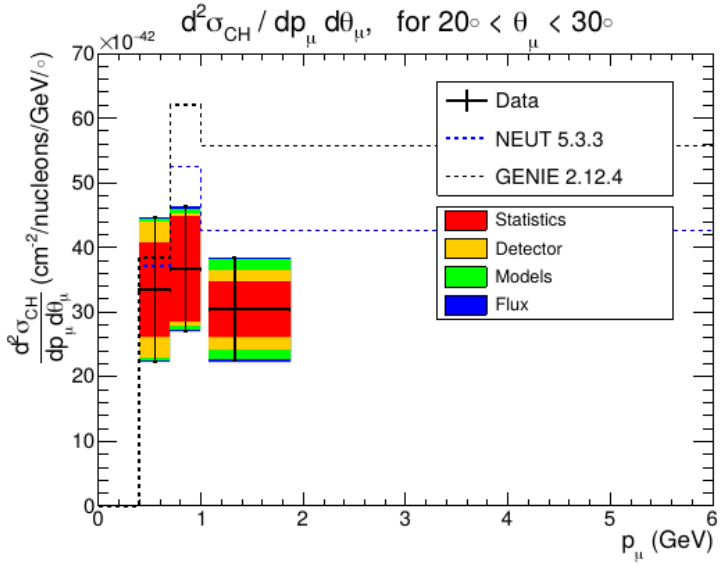
p_μ > 400 MeV/c $\cos(\theta_\mu) > 50^o$

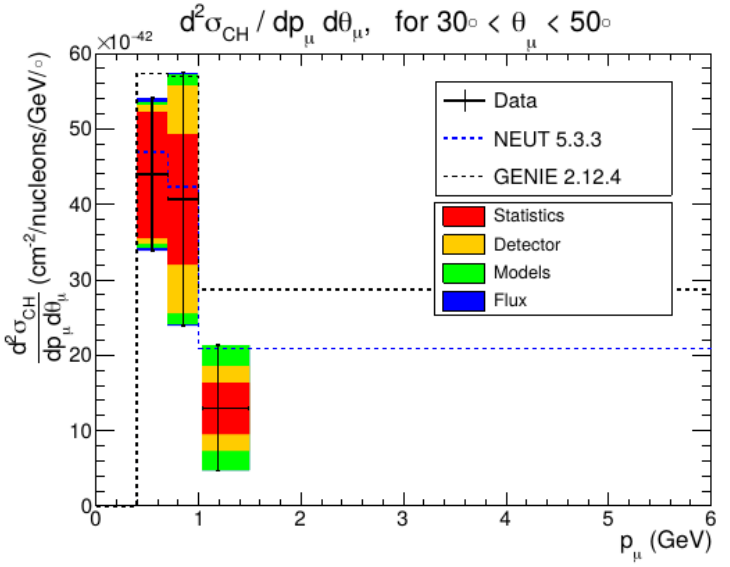
p_π > 400 MeV/c $\cos(\theta_\pi) > 50^o$

Results: CH Target



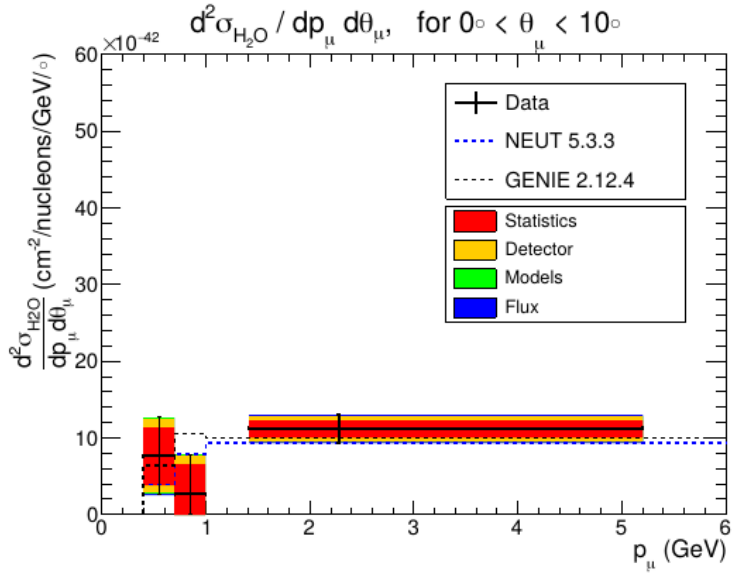


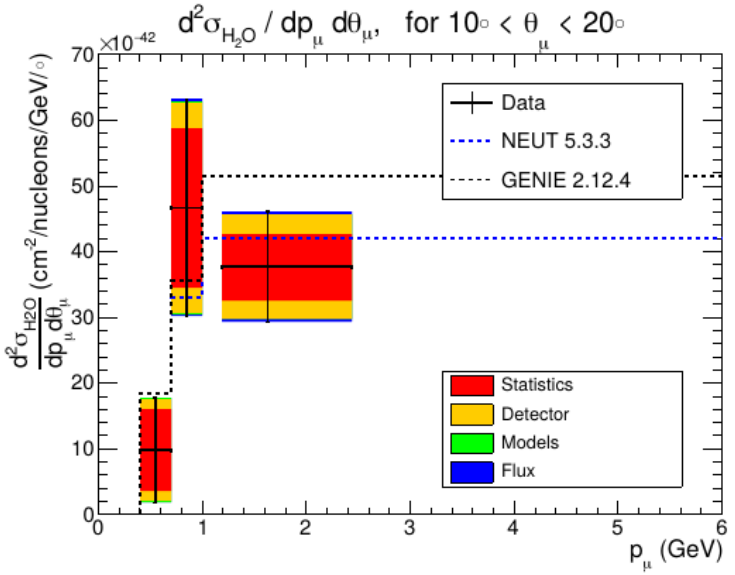


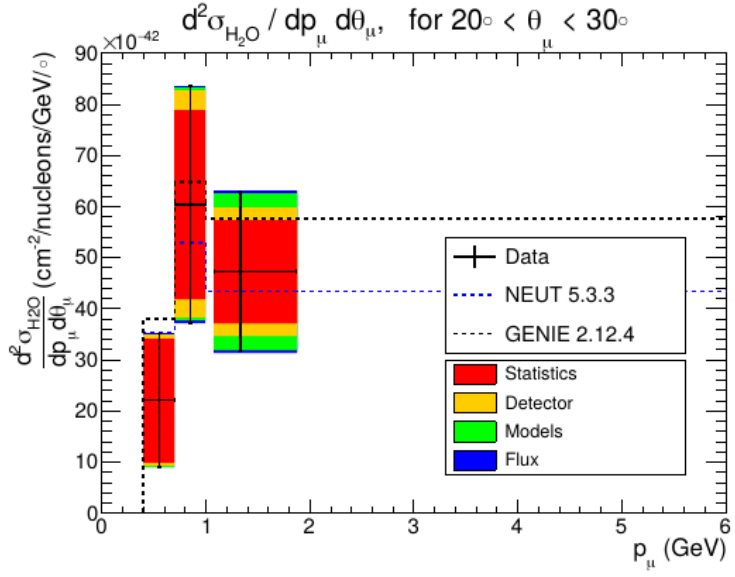


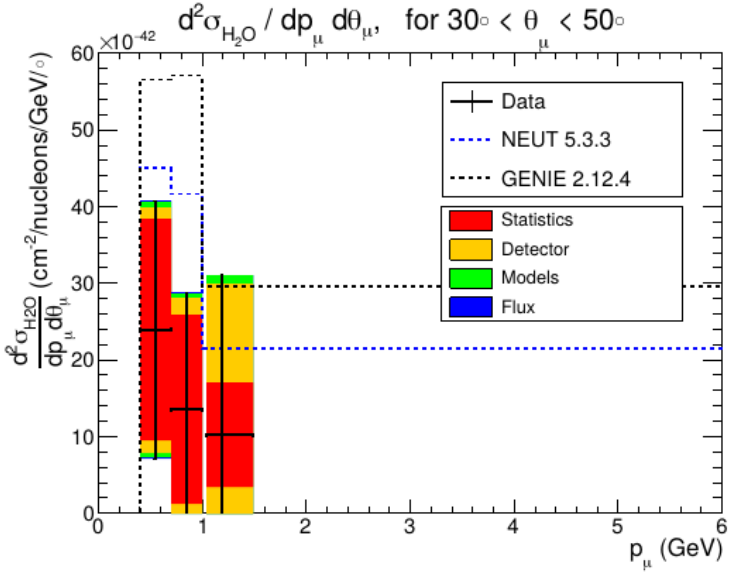
- Cross section on μ kinematics
- Cross section sits below NEUT prediction
- Shape agrees well

Results: H_20 Target





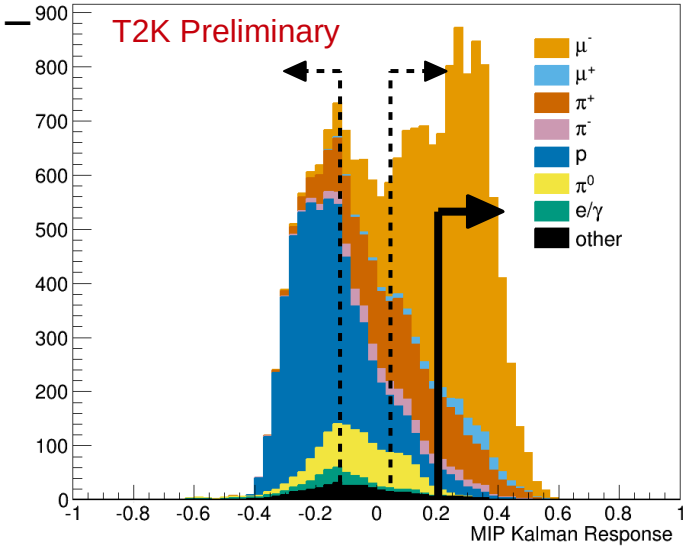




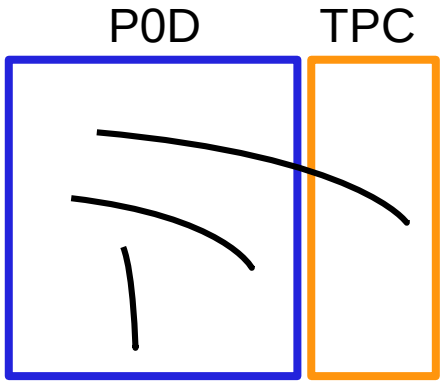
- Cross section on μ kinematics
- Cross section sits below NEUT prediction
- Shape agrees well

CC1π^+ in the P0D ($H_2$0+CH)

- Differential in p_μ-θ_μ
  - Projected into 2 x 1D
  - Results in p_μ and θ_μ are from a single fit
- Combined measurement on multiple targets:
  - CH + $H_2$0 + Brass

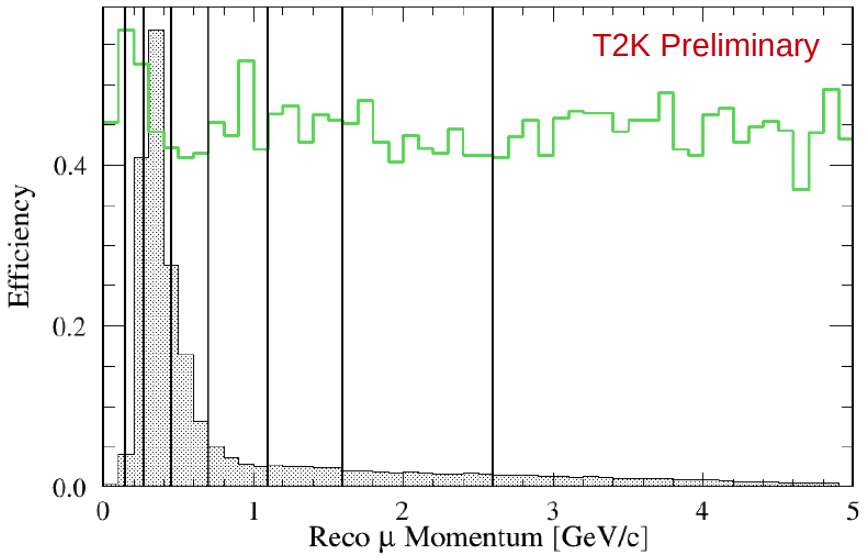


- Sideband samples
  - Constrain CC0π and DIS
  - Shape and normalization parameters
- Not unfolded:
  - Result in reco. μ kinematics
  - Difficult to compare to models

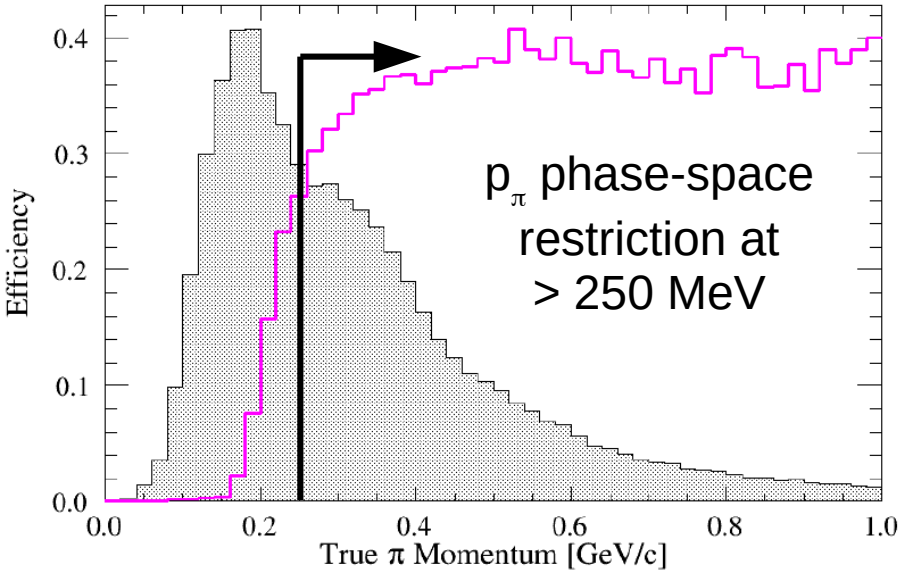


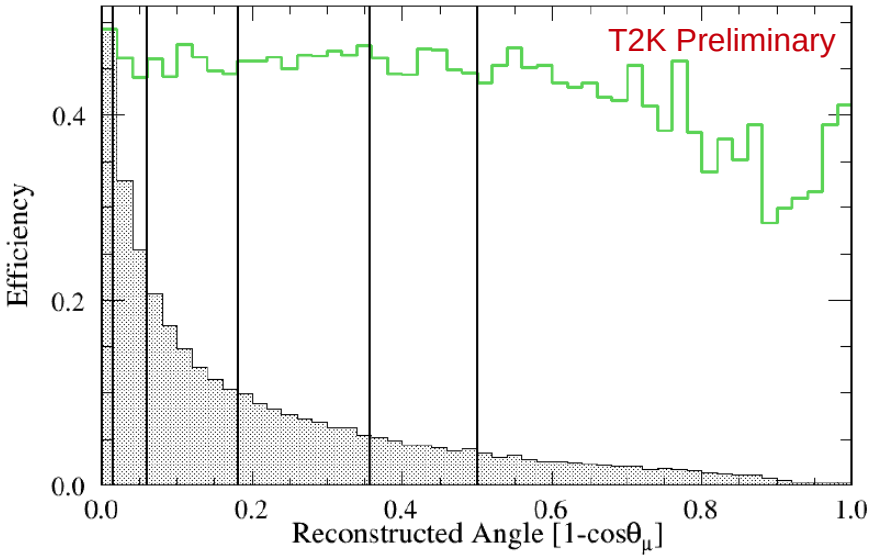
Track Topologies

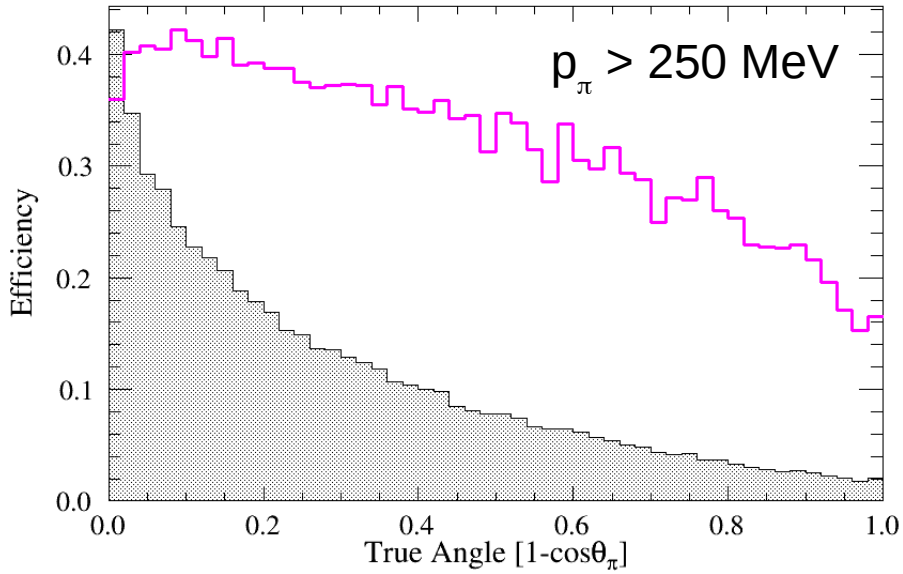
Efficiencies



T2K Preliminary

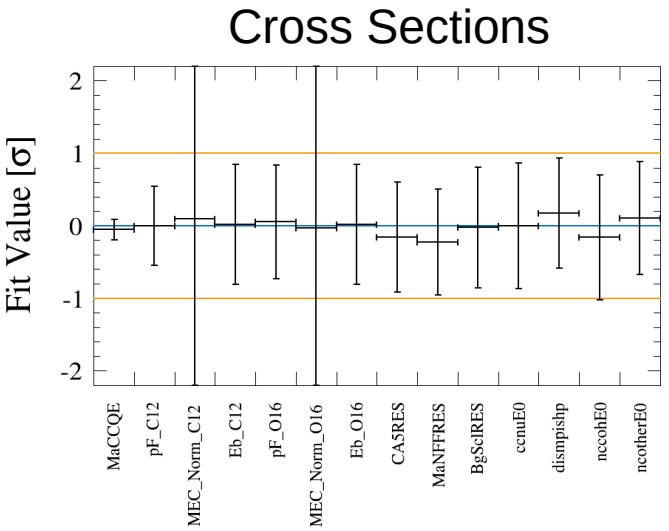


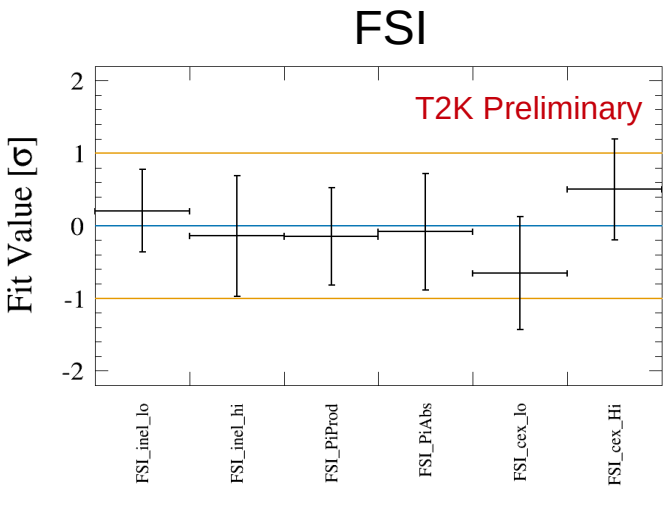


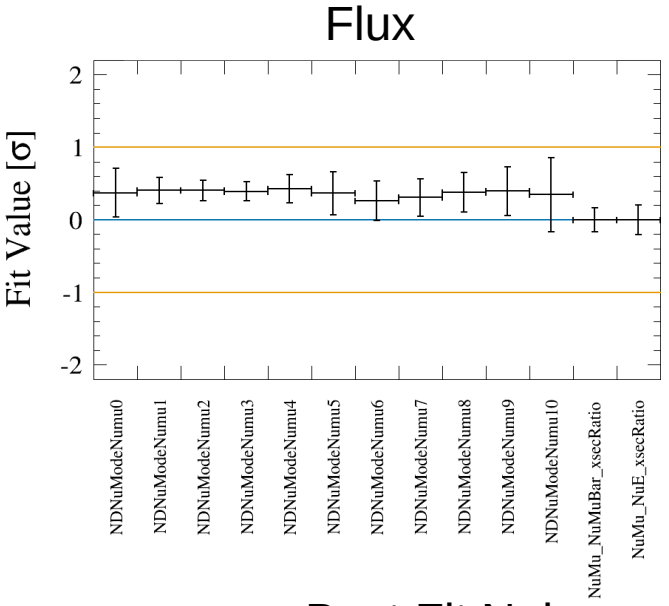


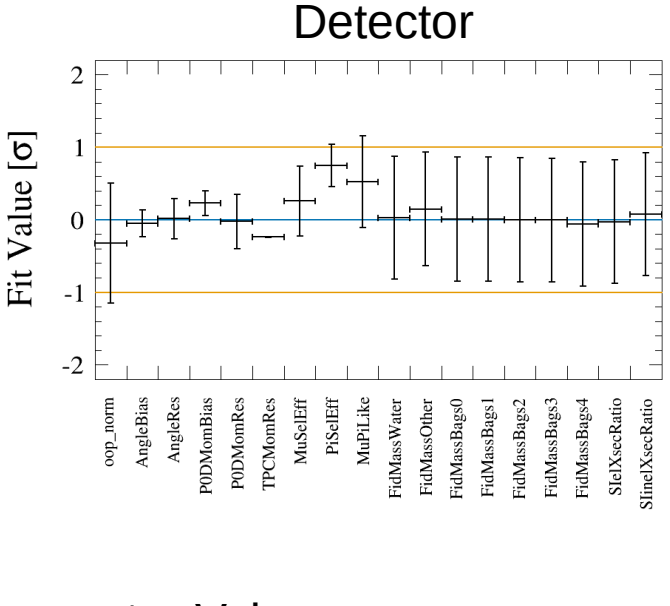
Data Fit Results

- Fairly insensitive to:
  - Most cross sections
  - FSI parameters
  - P0D mass uncertainties
- Constraints on:
  - M_A QE
  - p_μ-θ_μ resolution and bias
  - π selection efficiency
  - Flux: ~1.5% normalization increase
- Consistent with mock data study results



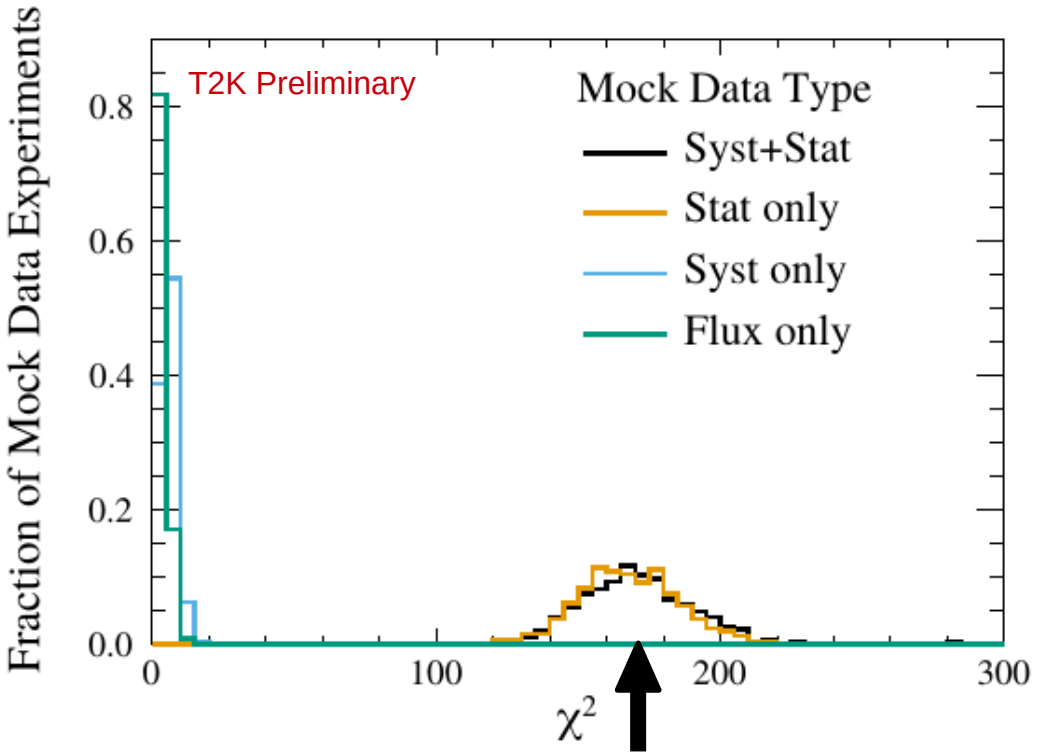






Best Fit Nuisance Parameter Values

Mock Data and Data χ^2



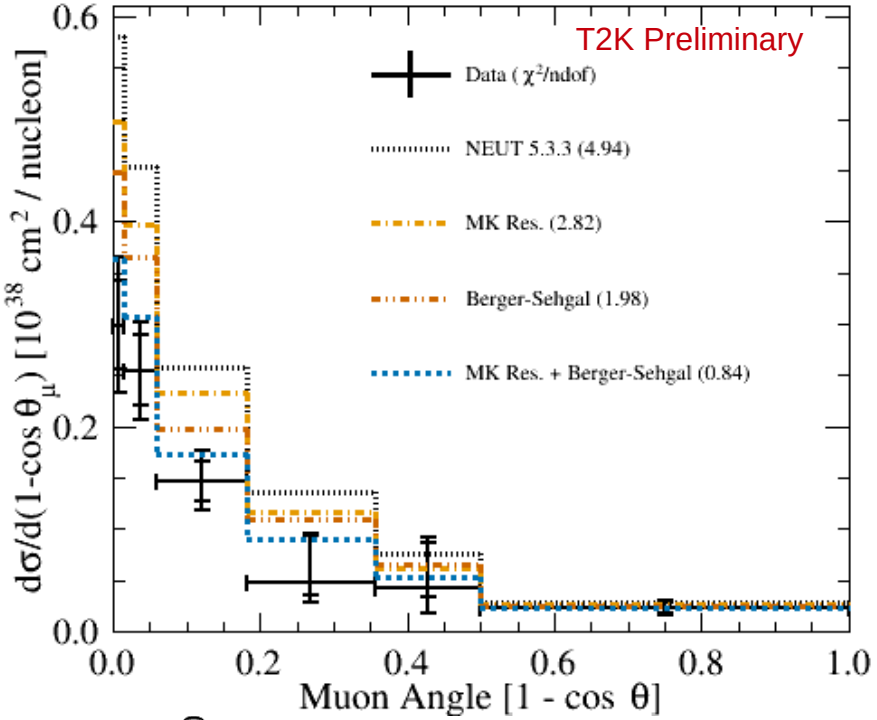
Mean χ^2 = 167

Data χ^2 = 172

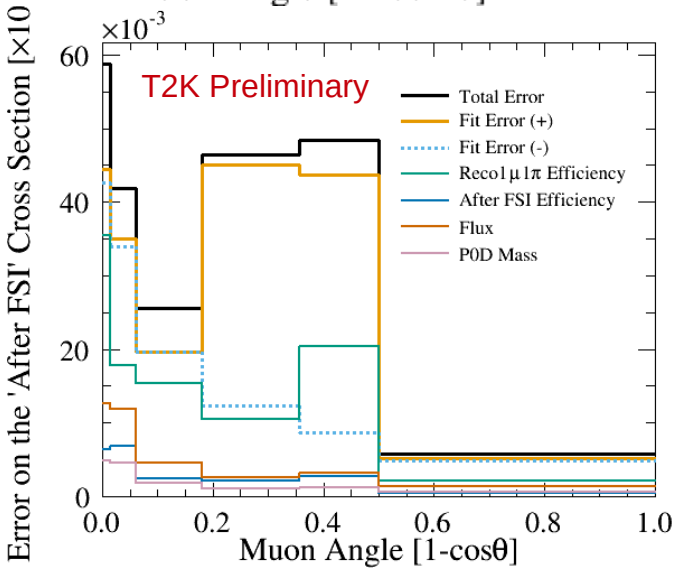
χ^2/ndof = 1.03

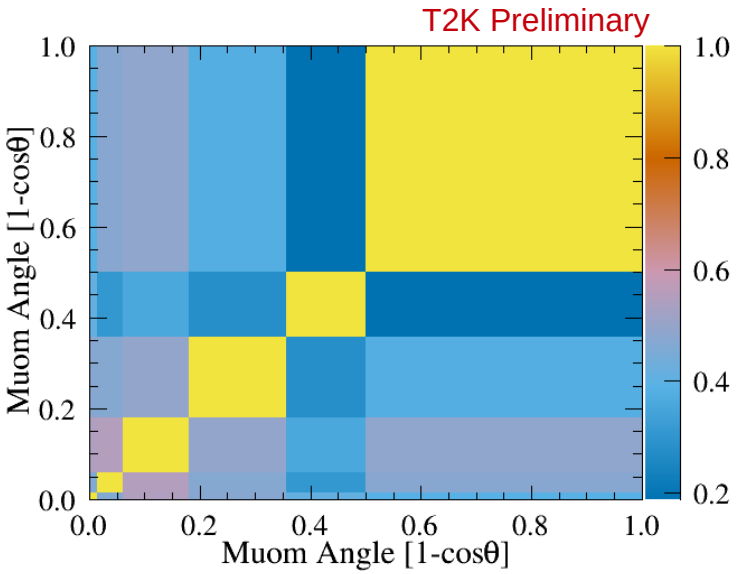
- Compare data fit with ensemble of Mock Data sets
- Random throws
  - Flux parameters
  - All systematics
  - Statistics
  - Statistics+systematics
- Mock data shows that results should be statistics limited
- **Data χ^2 agrees with random statistical(+syst) fluctuation**

$d\sigma/d(1-\cos\theta_\mu)$ $1\mu1\pi$ After FSI

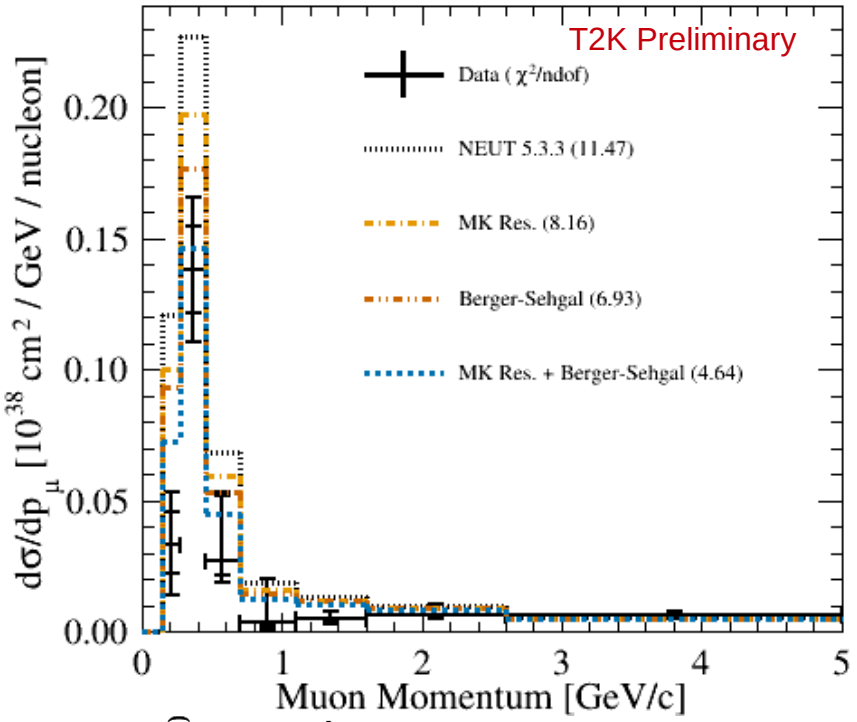


- Result for p_π > 250 MeV
- Sits well below NEUT prediction
- Agreement improves at higher angle
- Agreement improves for newer models (B-S, MK)

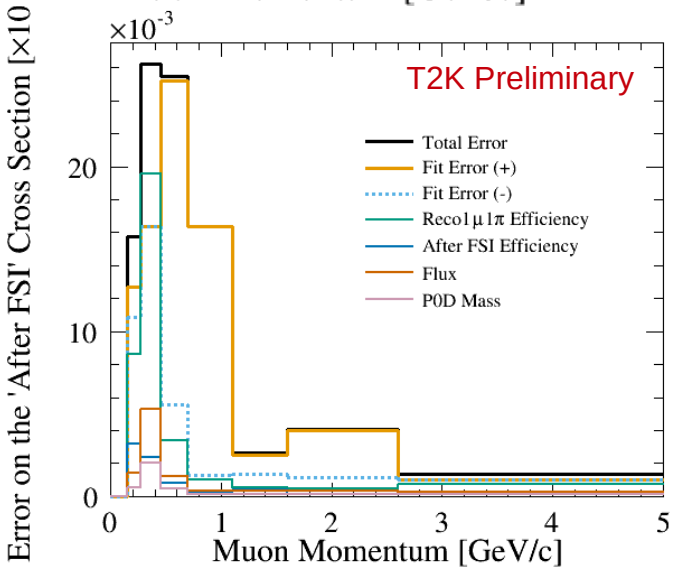


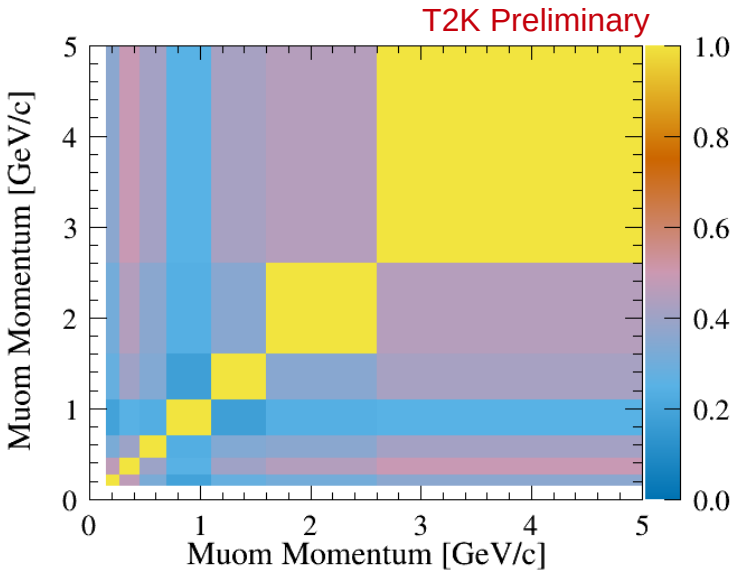


$d\sigma/dp_\mu$ $1\mu1\pi$ After FSI



- Result for p_π > 250 MeV
- Sits well below NEUT prediction
- Agreement improves at higher momentum
- Agreement improves for newer models (B-S, MK)

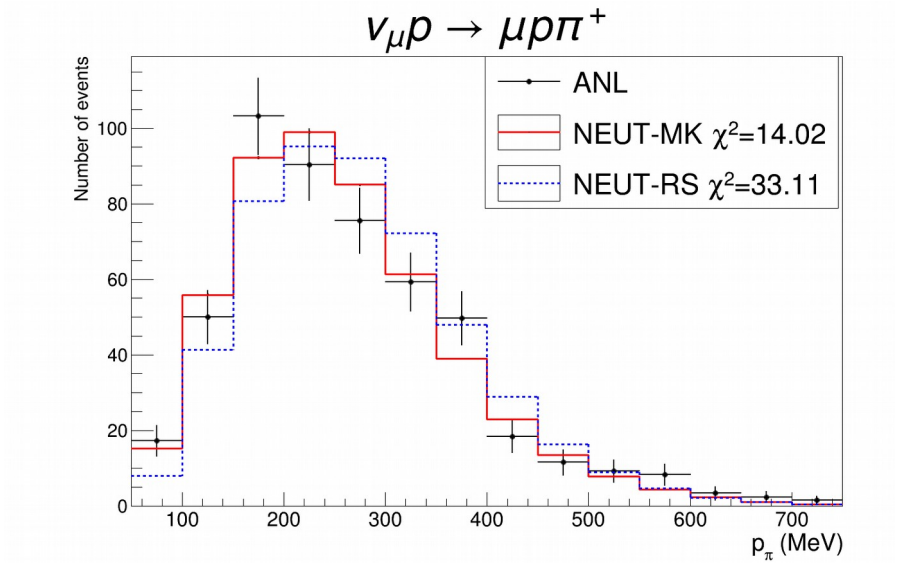


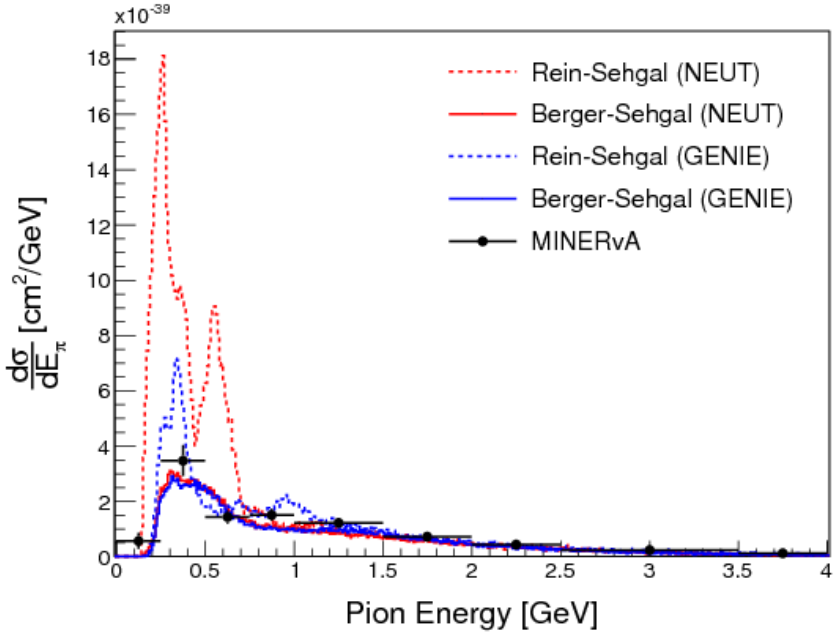


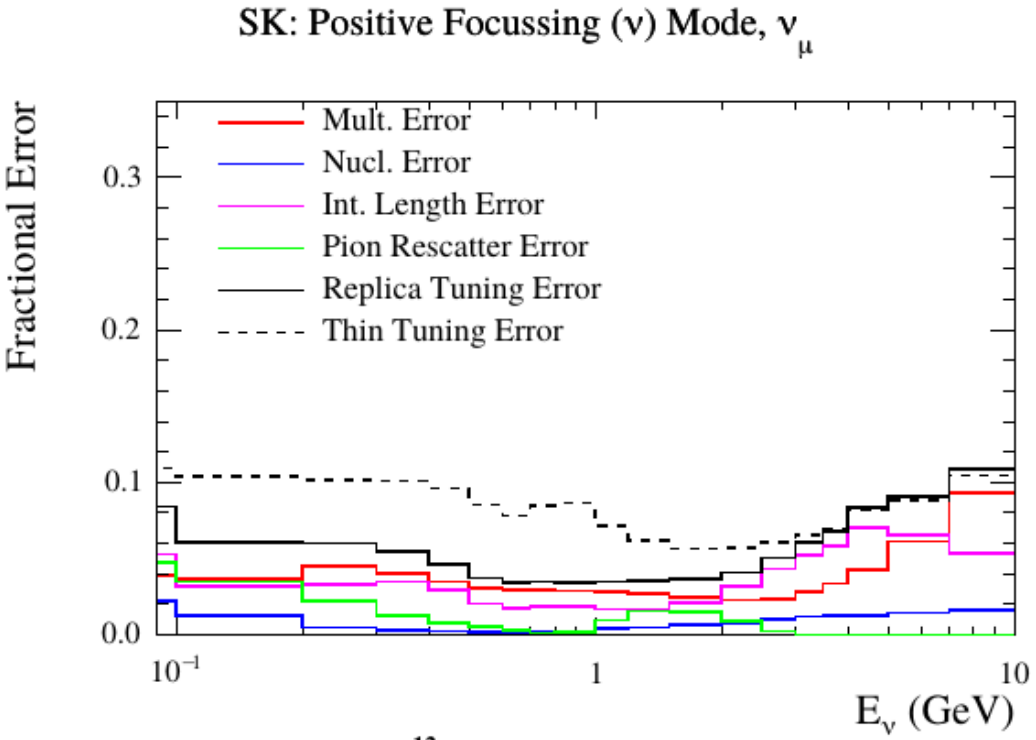
In the works

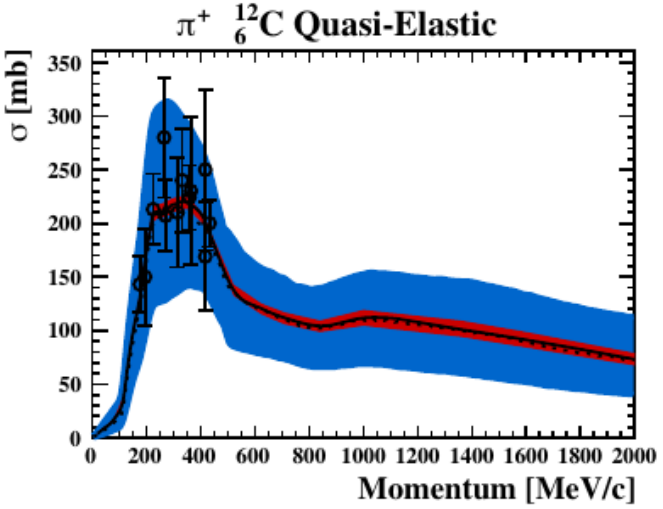
- Measurements:
  - CCν π^+ on H_20 (FGD2)
    - Improved phase space
    - Promising studies on Michele momentum reconstruction
  - CC$\bar{\nu}$ π^- on CH (FGD1)
  - CC$\bar{\nu}$ π^- on H_20 (FGD2)
  - CCν π^+ p on CH (FGD1)
    - Tracked p allows transverse variable reconstruction
    - Possible to separate C and H
    - Small phase space
    - Large backgrounds
- Analysis improvements:
  - Combined fits:
    - CH+H20, ν+$\bar{\nu}$
    - CC0π + CC1π + 4π acceptance
  - Likelihood fitter
    - No more D'Agostini
    - Controlled regularization
  - New flux estimate / errors
  - New cross section systematics
    - DIS/SIS region
    - π Secondary interactions
    - Nucleon FSI
  - New π production models
    - Coherent B-S
    - Resonant MK

Analysis Improvements



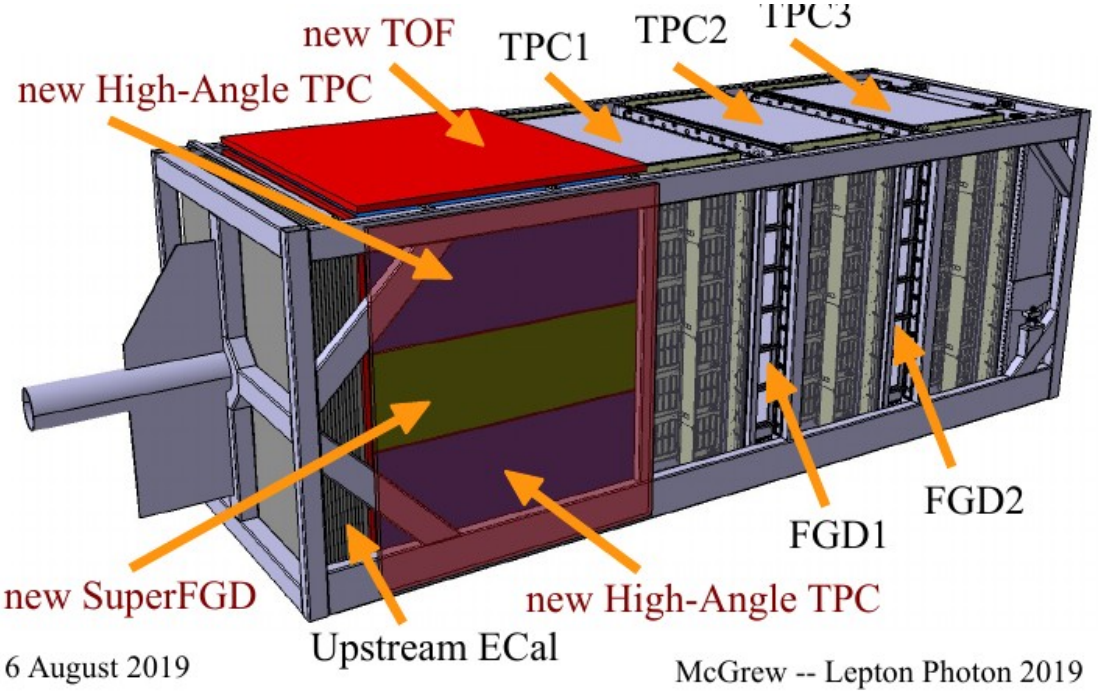






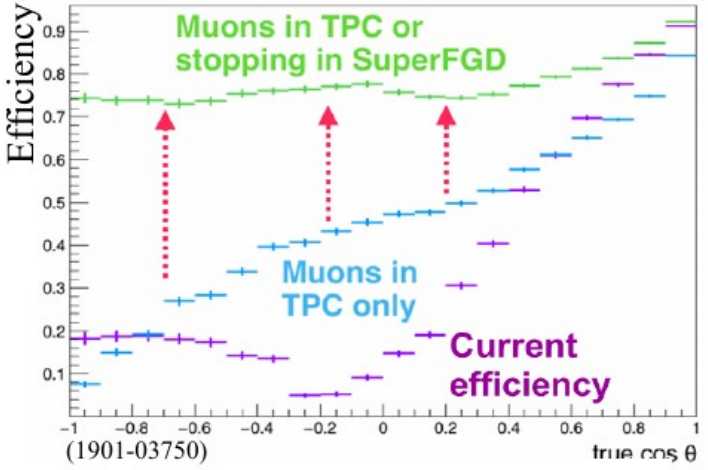
Future: ND280 Upgrade

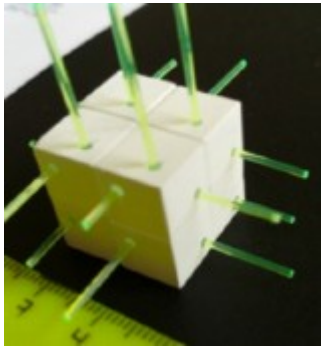
- Remove P0D and add SuperFGD
  - High-res 3D scint. detector
  - Sandwiched between TPCs
- Lower thresholds
- 4π(ish) acceptance
- Still hard to reco pions
- Installation in 2021



		# of events (/10^{21} POT)	Purity (%) CC0π	CC1π	CC Other
current	FGD 1	50507	72.5%	64.0%	68.2%
	FGD 2	50125	71.5%	62.3%	63.8%
upgrade	FGD 1	52655	72.9%	64.1%	64.7%
	FGD 2	51460	71.6%	62.9%	63.3%
	SuperFGD	95490	72.5%	70.3%	72.7%

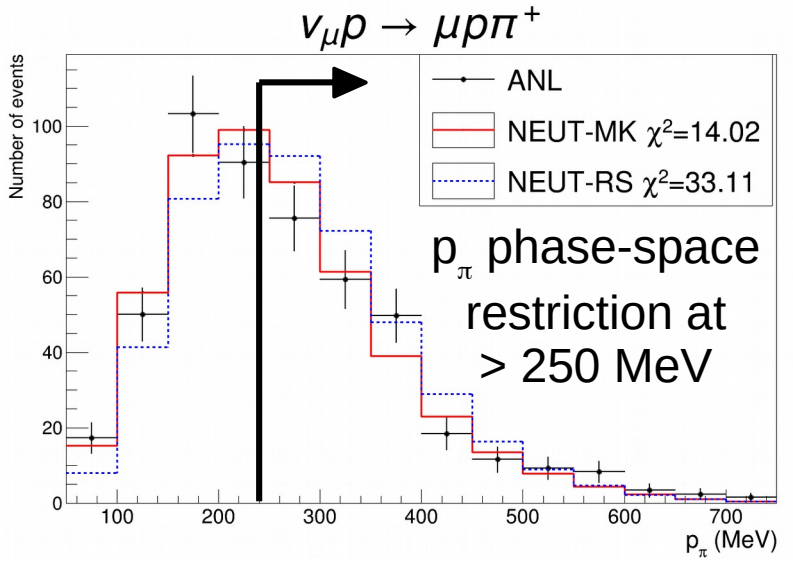
Efficiency to measure muon vs direction

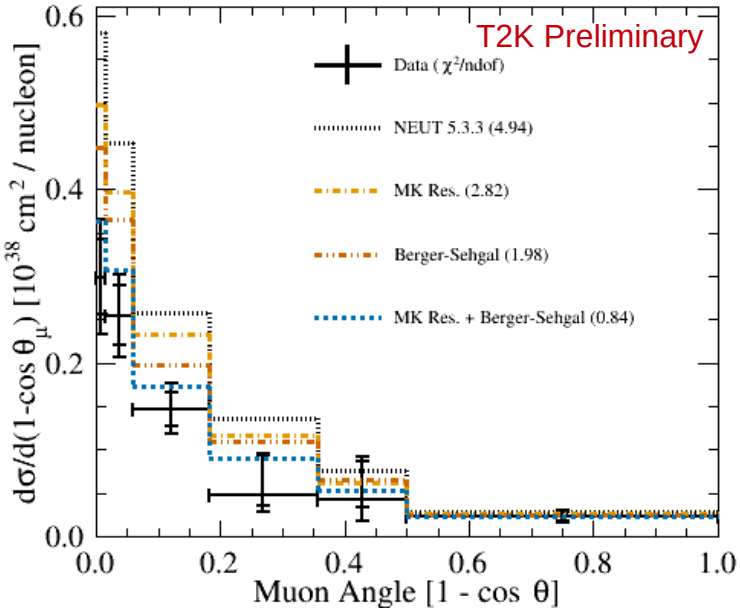




Summary and Conclusions

- Four T2K CC1π^+ cross section measurements were presented
- Central themes:
  - The general shape of the μ kinematics agree
  - When π low momentum phase space is restricted: data is below predictions
  - When π low momentum phase space is restored: normalization is recovered
- Improved measurements are in the works
- Detector upgrade has been approved: coming in 2021





Thank you for your attention.

Questions?

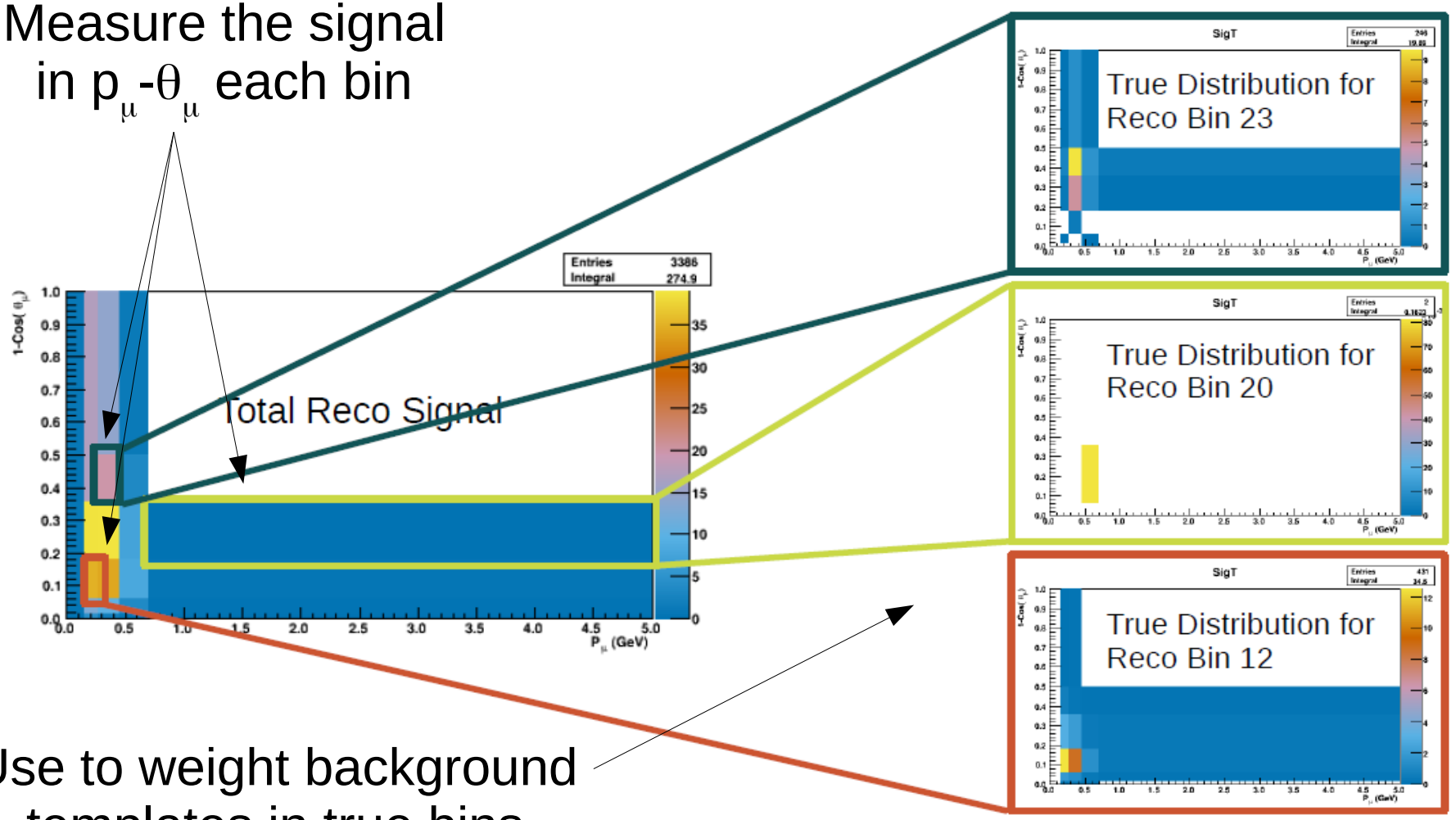
Backup Slides

Avoiding Signal Model Dependence

- Signal definition
- Event selection technique
- Constraining backgrounds with sidebands
- Signal-like background treatment
- Efficiency corrections

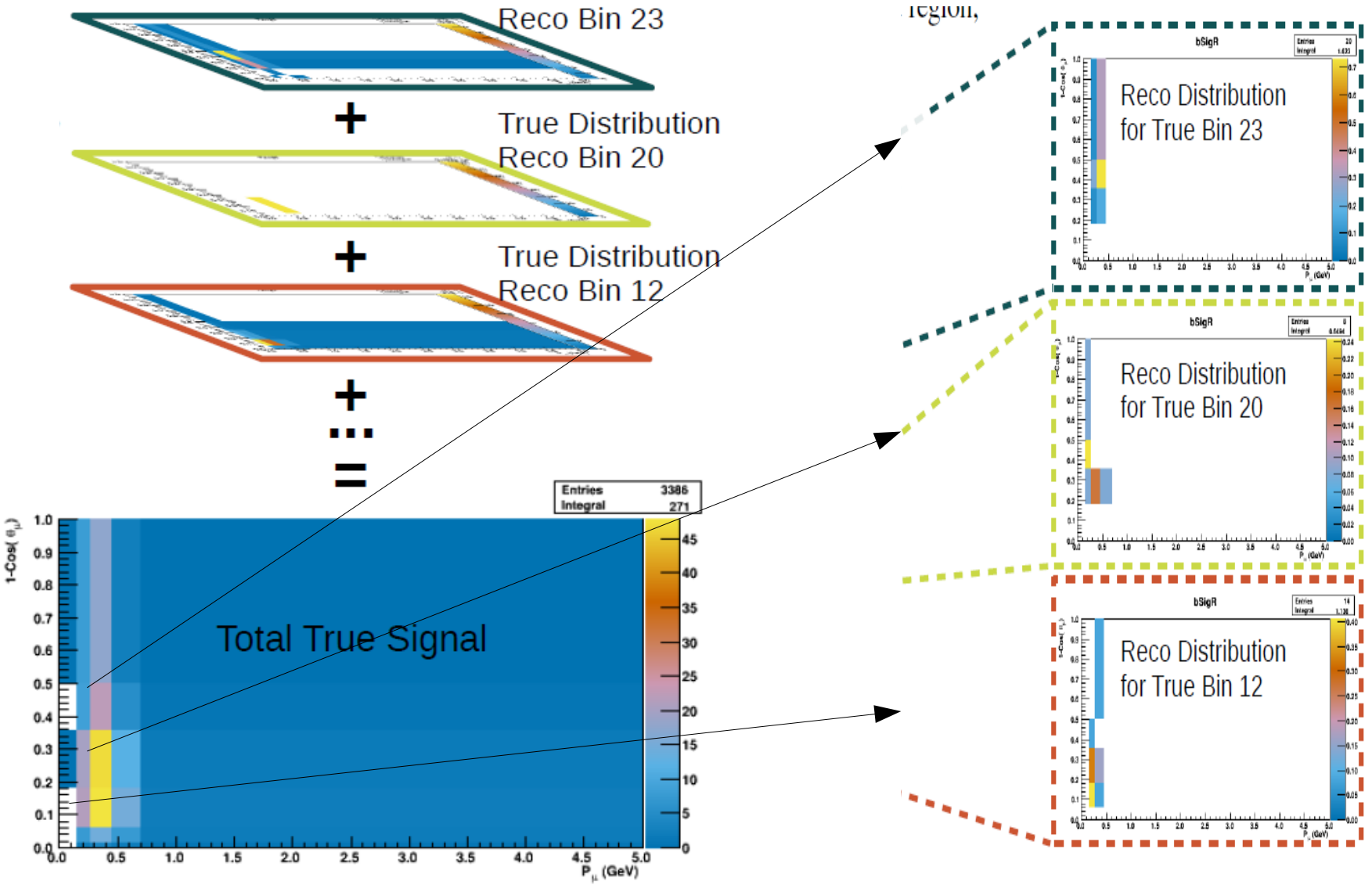
Signal-like Backgrounds

Measure the signal in p_μ-θ_μ each bin

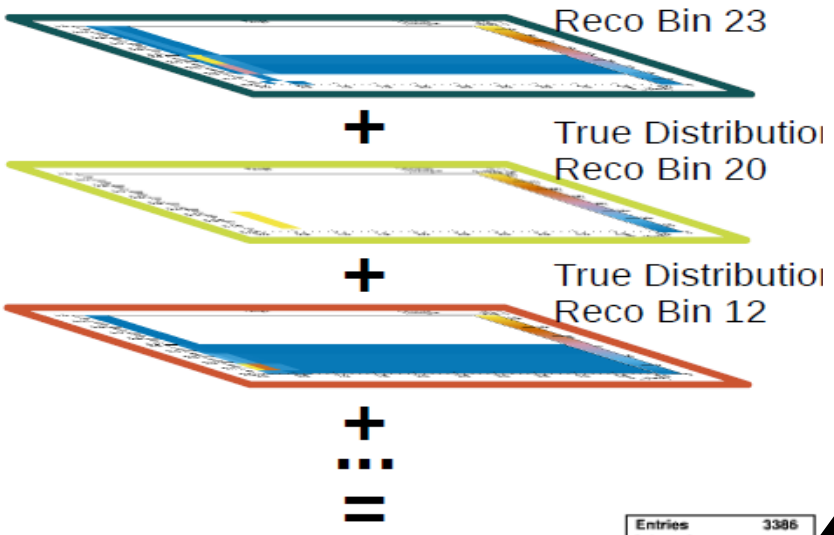


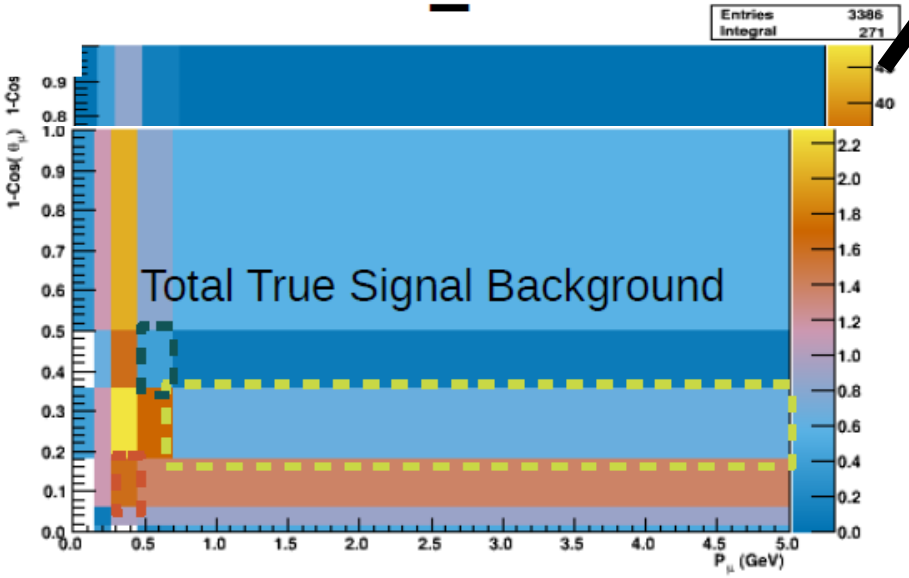
Use to weight background templates in true bins

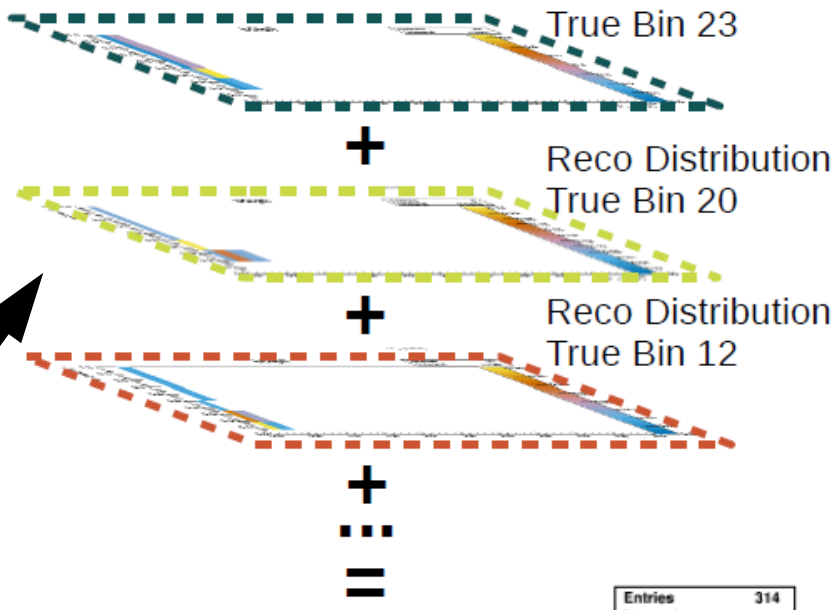
Signal-like Backgrounds

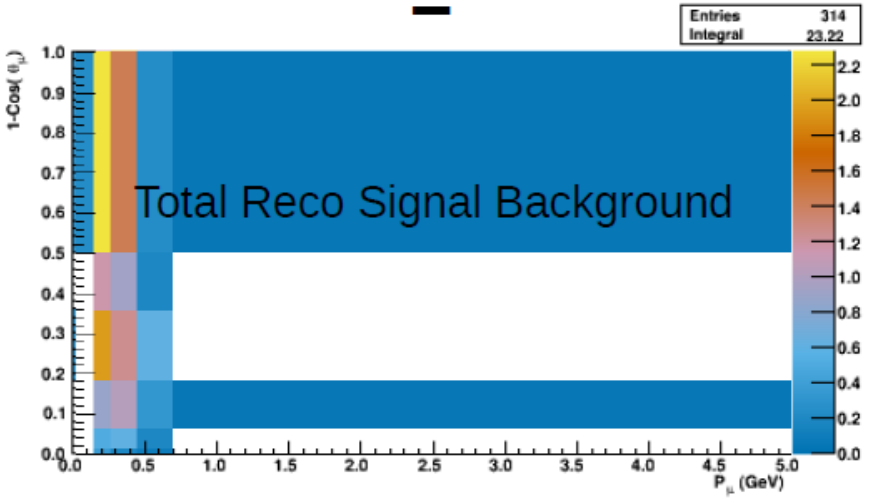


Signal-like Backgrounds

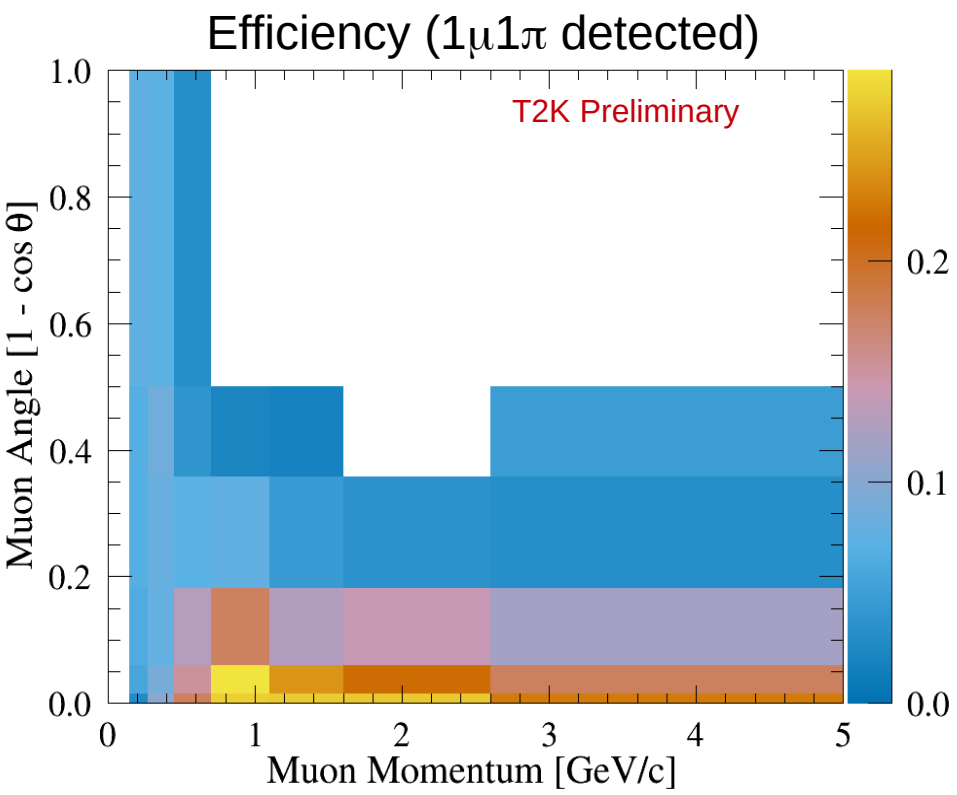


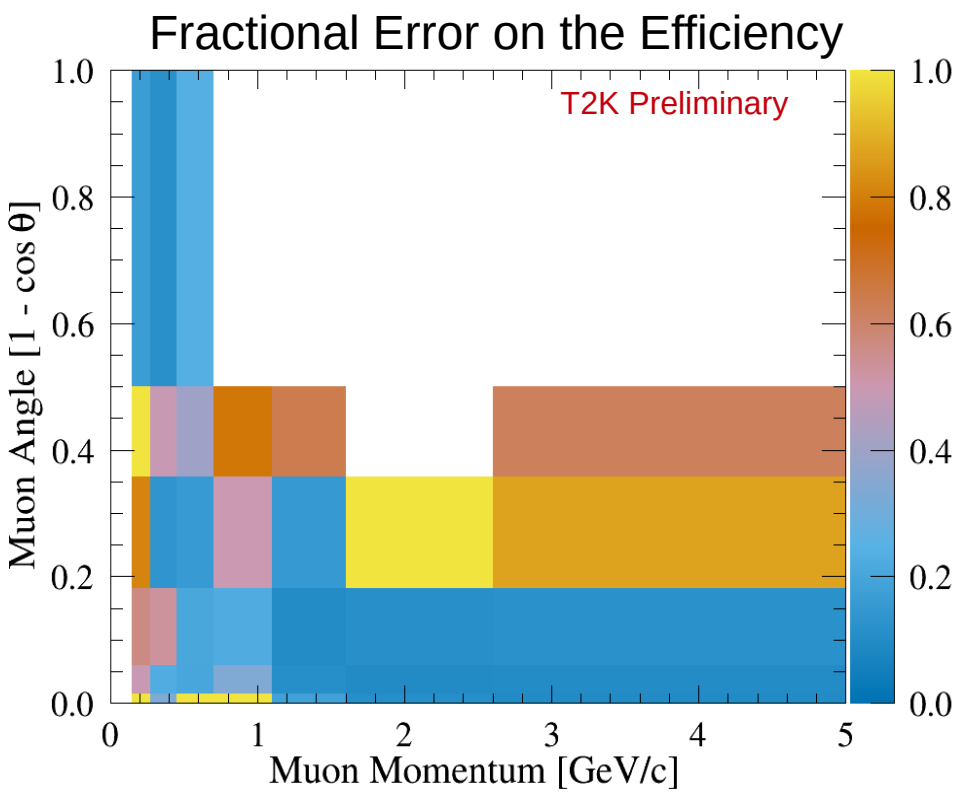






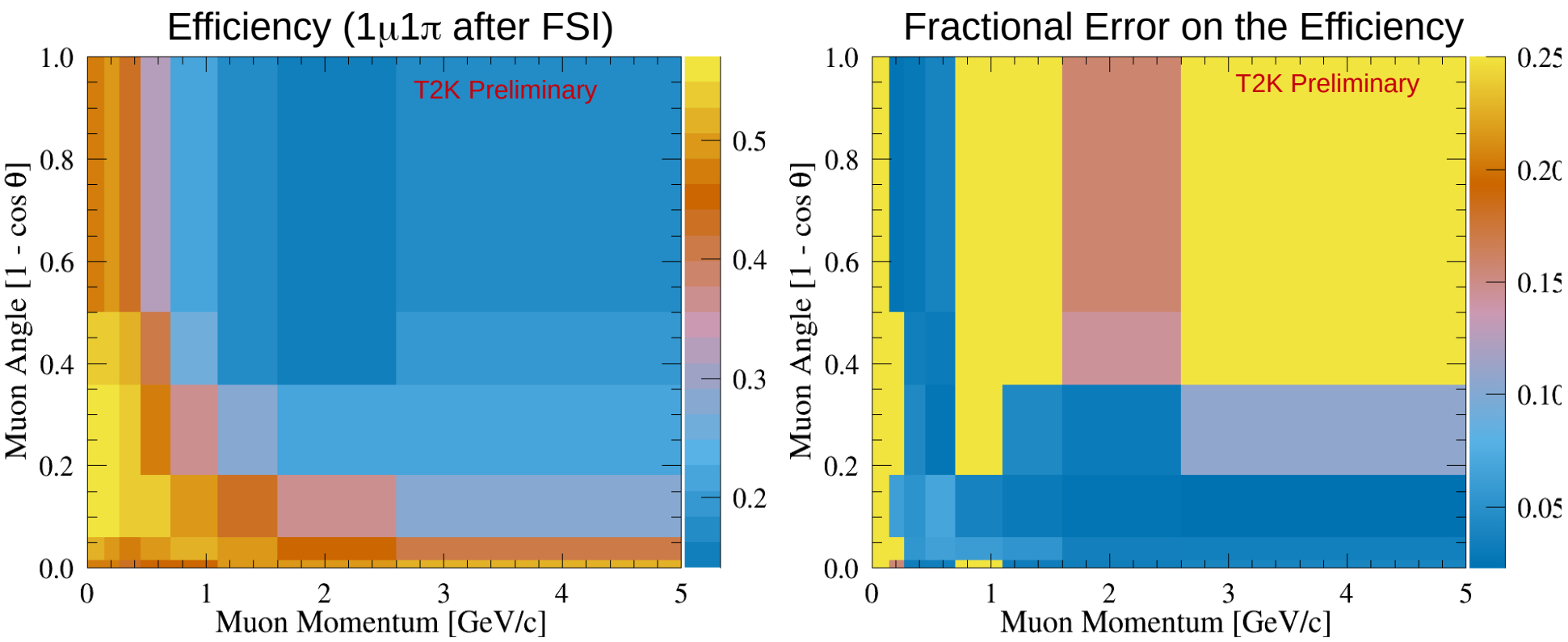
Efficiency Corrections (1μ1π detected)





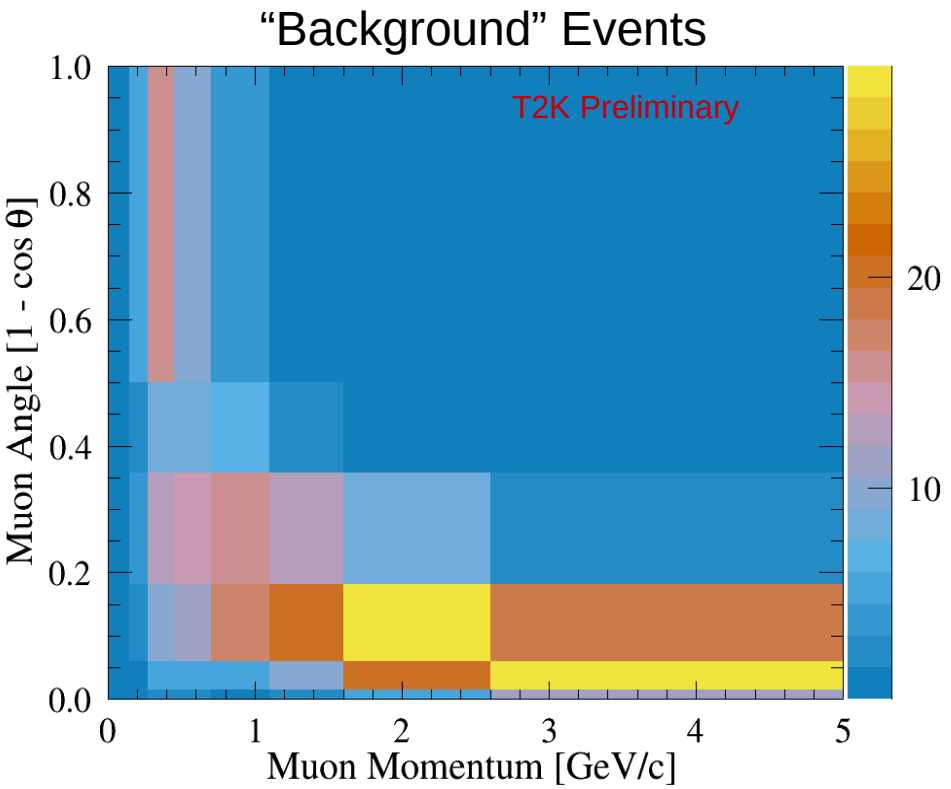
Efficiency for the 1μ1π detected signal definition, and associated uncertainties

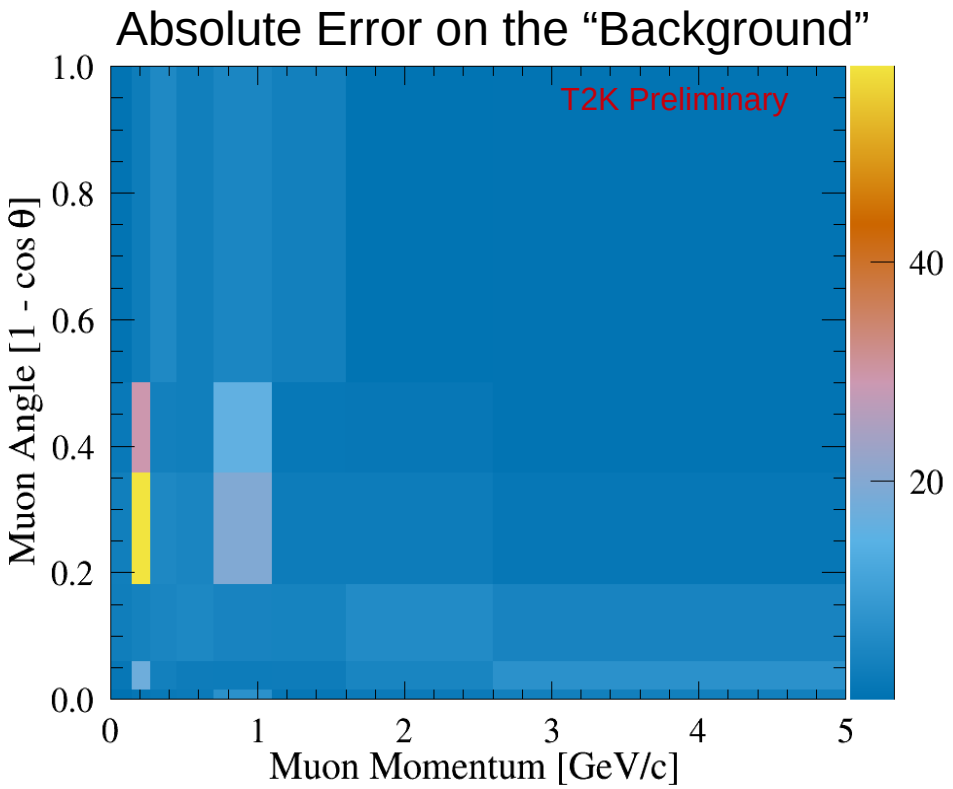
Efficiency Corrections (1μ1π After FSI)



Efficiency for the 1μ1π afterFSI signal definition, and associated uncertainties

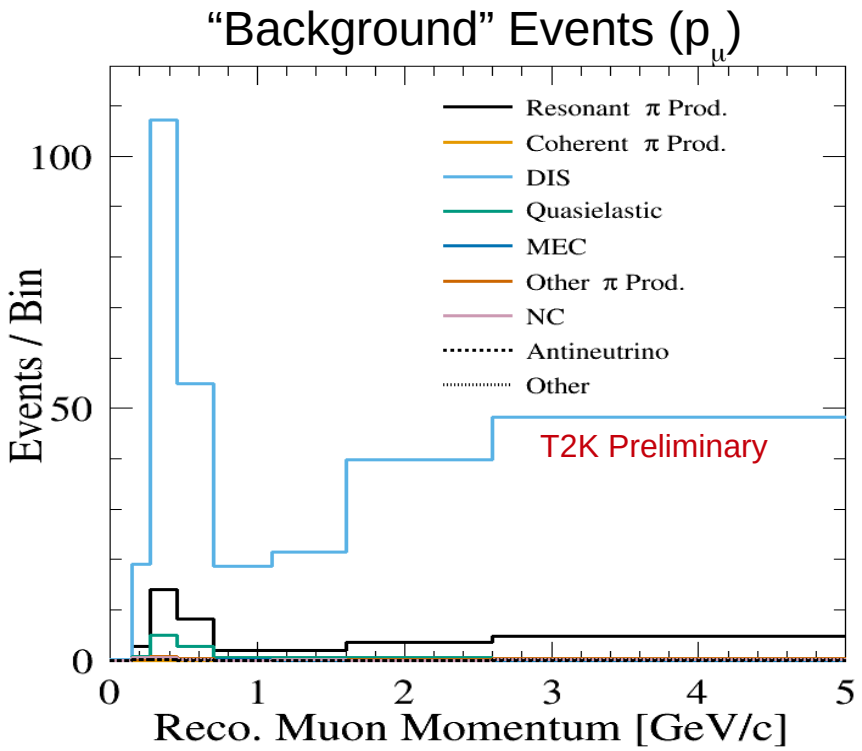
$1\mu 1\pi$ detected ≠ $1\mu 1\pi$ after FSI

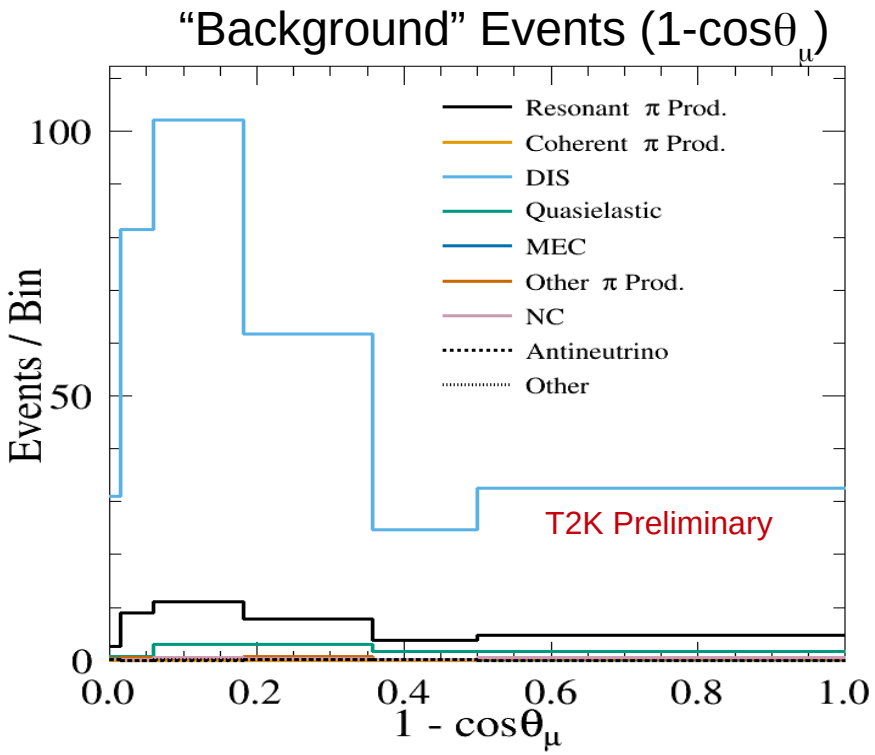




Events that pass sig def 1 but not sig def 2, and must be subtracted to convert from sig def 1 but to sig def 2

$1\mu 1\pi$ detected ≠ $1\mu 1\pi$ after FSI



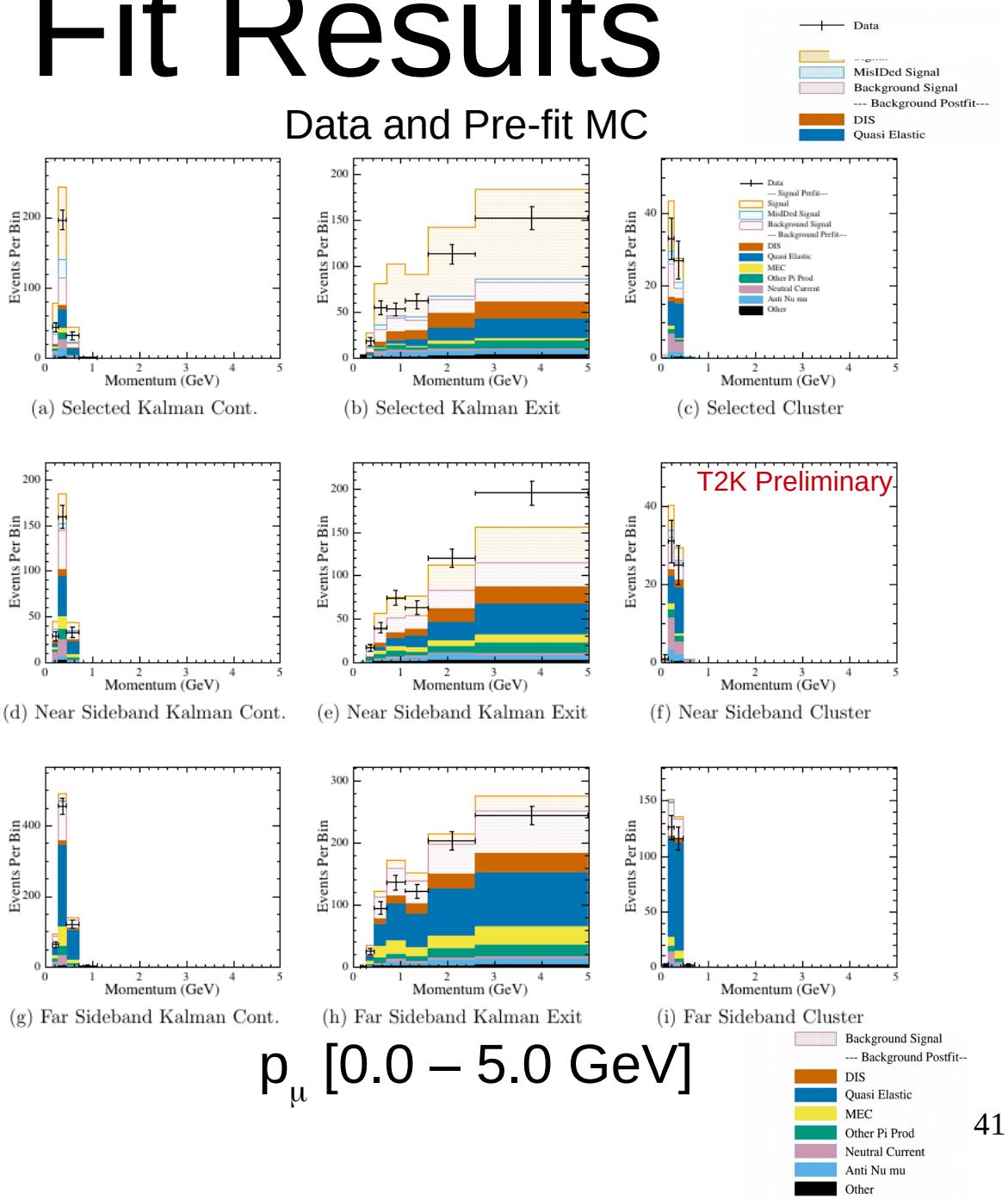


Breakdown by interaction type of events that pass sig def 1 but not sig def 2, and must be subtracted to convert from sig def 1 but to sig def 2

Data Fit Results

- Prefit MC greatly overestimates the data
- Overestimate roughly flat
- The size of discrepancy decreases with the amount of signal predicted

Data and Pre-fit MC

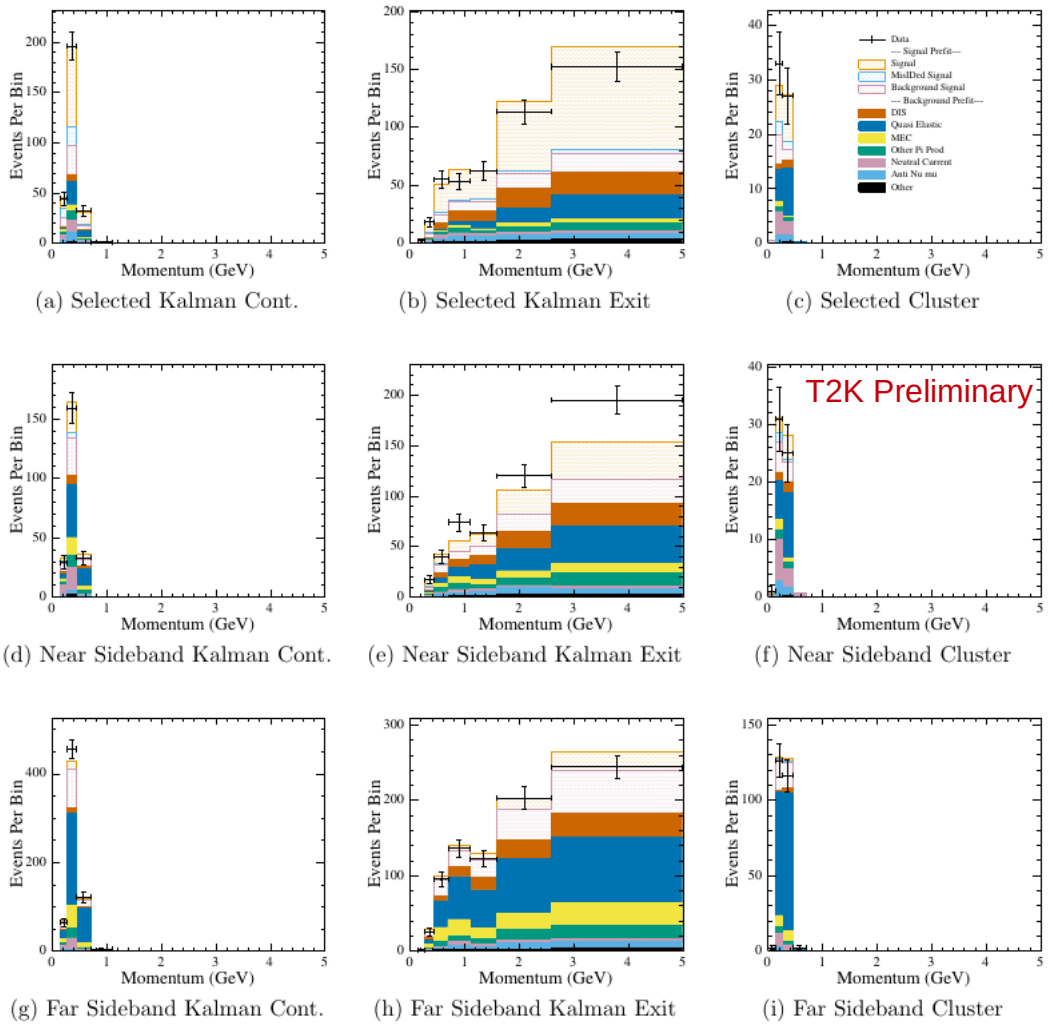


p_μ [0.0 – 5.0 GeV]

Data Fit Results

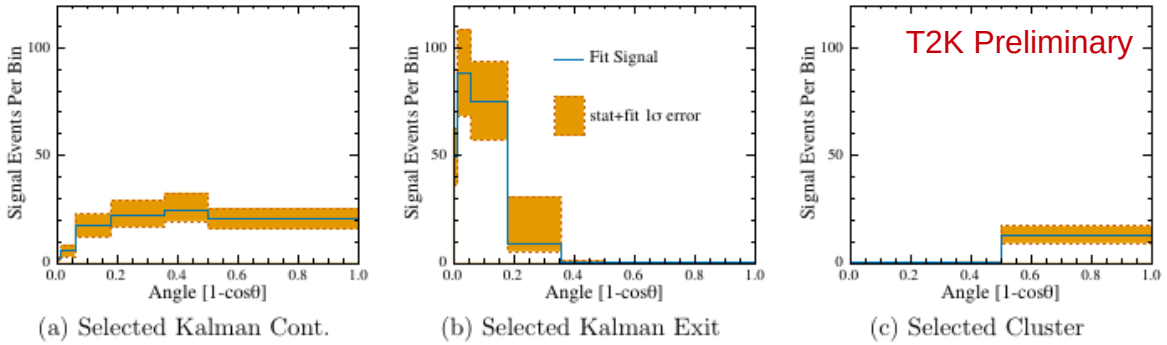
- Post-fit MC agrees well with data
- Almost all bins within 1σ error band
- Fraction with >1σ discrepancy consistent with expectations given number of bins
- Some tension between the Kalman Exiting Selected and Near Sideband samples
- Tension is at high momentum

Data and Pre-fit MC

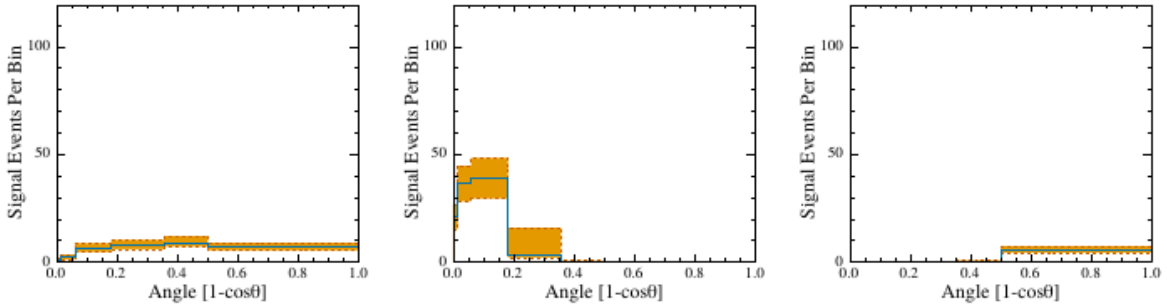


p_μ [0.0 – 5.0 GeV]

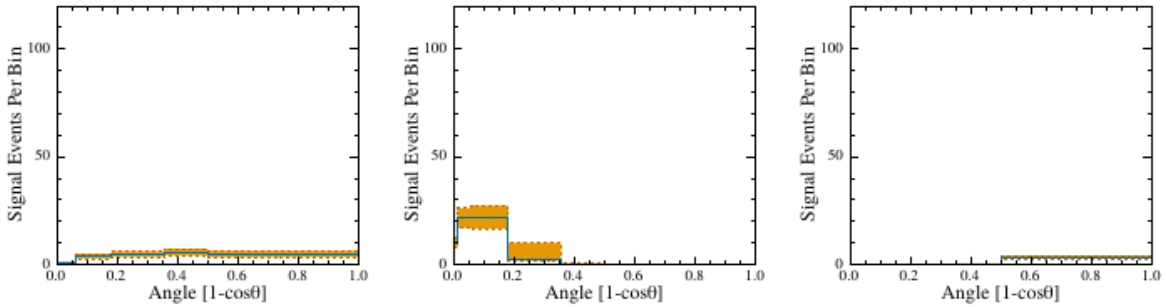
Data Fit Results



(a) Selected Kalman Cont. (b) Selected Kalman Exit (c) Selected Cluster



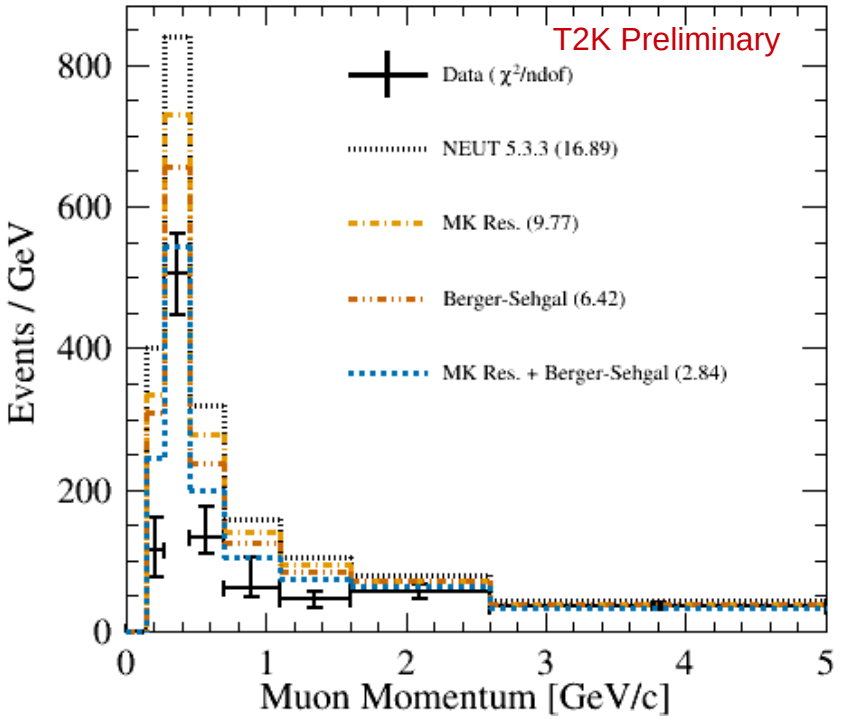
(d) Near Sideband Kalman Cont. (e) Near Sideband Kalman Exit (f) Near Sideband Cluster



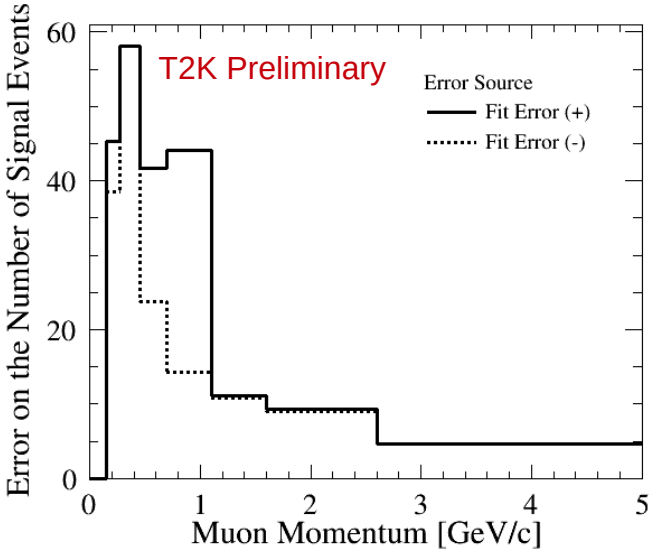
(g) Far Sideband Kalman Cont. (h) Far Sideband Kalman Exit (i) Far Sideband Cluster

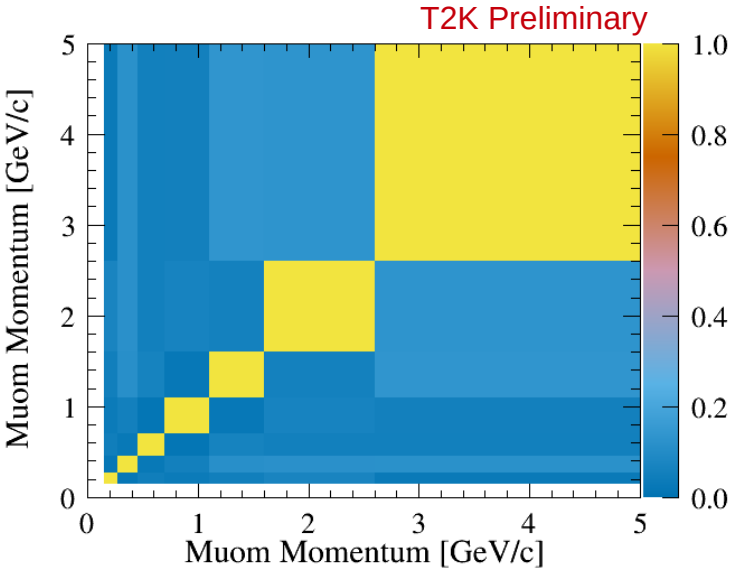
Extracted Signal Events and Fit Errors

Event Rate Comparisons

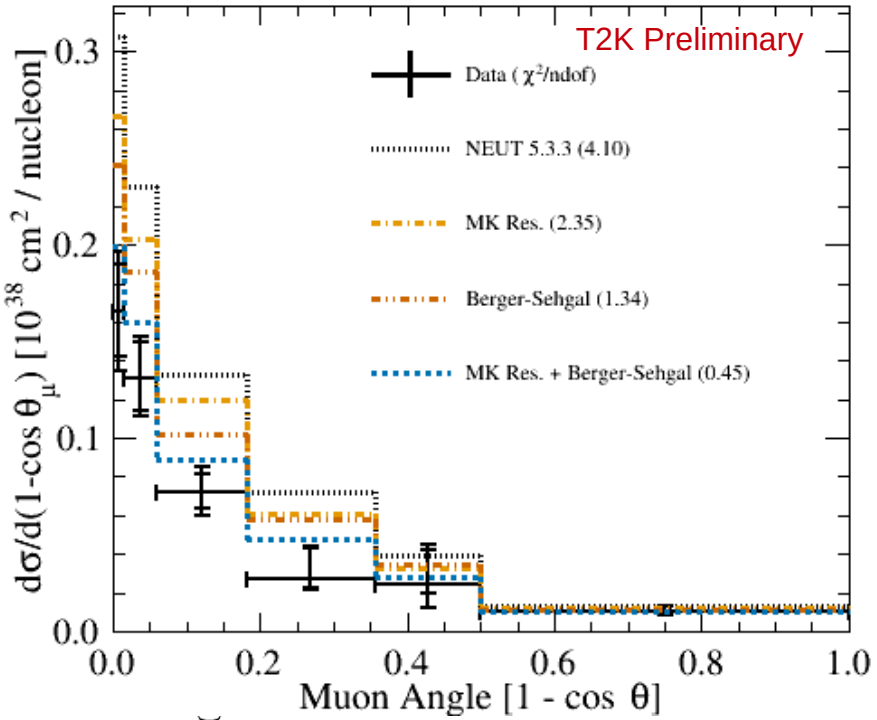


- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS → MK
  - NEUT with coh RS → BS
  - NEUT with both changes
- Track errors and correlations

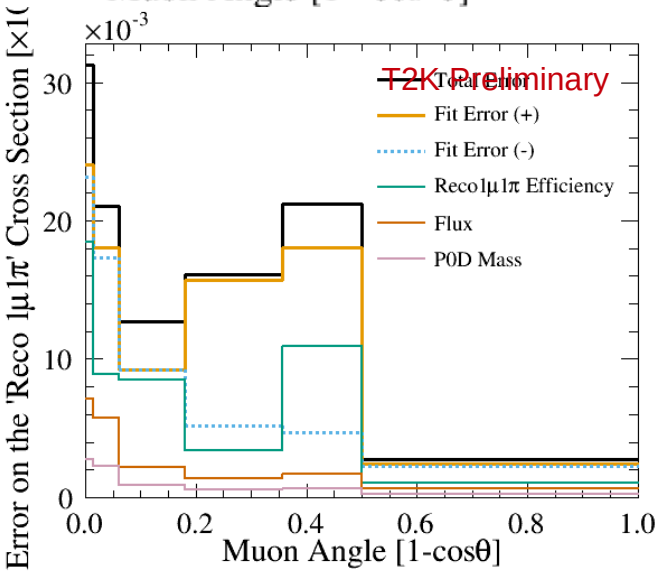


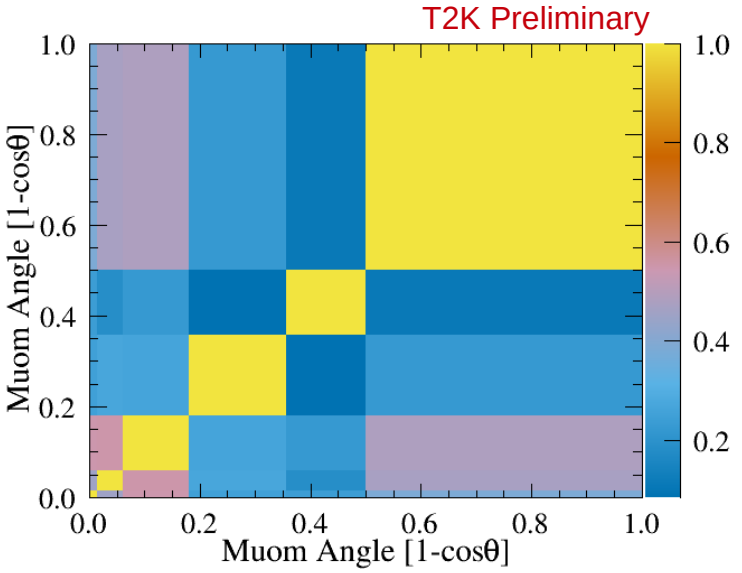


1μ1π Detected Cross Section

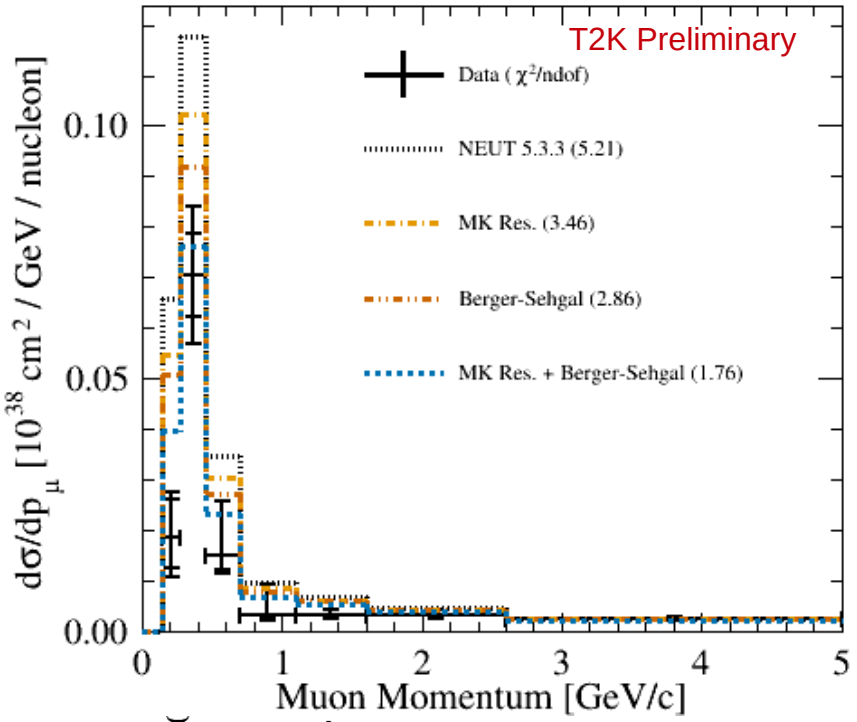


- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
- Track errors and correlations





1μ1π Detected Cross Section



- Compare data with various models
  - NEUT 5.3.3
  - NEUT with res RS→MK
  - NEUT with coh RS→BS
  - NEUT with both changes
- Track errors and correlations